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Treatment Effectiveness for the Removal of Selected Contaminants from Drinking Water

Ralph Stone and Company, Inc., Los Angeles, California

Prepared for

Environmental Protection Agency, Washington, D C Div of Water Supply

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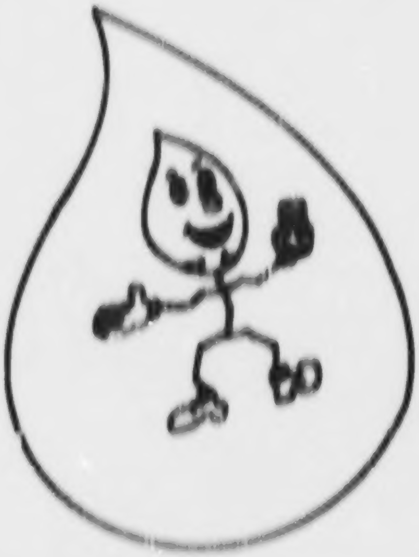
FINAL REPORT



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Coagulation
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Cobalt
Lithium
Molybdenum
Nickel
Tungsten
Vanadium
Bis-ethers
Polychlorinated Biphenyls
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By

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Prepared For
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ABSTRACT

An extensive literature survey was conducted to determine treatment methods for removing antimony, beryllium, bis-ethers, chlorinated hydrocarbon insecticides, cobalt, lithium, molybdenum, nickel, organophosphorus insecticides, polychlorinated biphenyls, tungsten, and vanadium from drinking water. The processes discussed included adsorption, chemical oxidation, coagulation/precipitation, distillation, electrodialysis, ion exchange, radiochemical degradation, reverse osmosis, and ultrafiltration. Treatment efficiencies were determined in terms of influent and effluent concentrations for each applicable treatment method. Process designs, constraints and limitations, operating conditions, and costs were presented for each treatment process discussed. Each process was evaluated as to its availability, applicability, and technical and economic feasibility. The best available and best technically feasible treatment processes were presented for each contaminant.

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SUMMARY

An extensive six-month literature survey was conducted for the Environmental Protection Agency, Washington, D. C., to determine treatment methods and efficiencies for removing certain selected contaminants from drinking water. The purpose was to present a list of useful processes which could assist in advanced technical planning for the removal of certain contaminants from drinking water. The contaminants studied were antimony, beryllium, bis-ethers, chlorinated hydrocarbon insecticides, cobalt, lithium, molybdenum, nickel, organic phosphorus insecticides, polychlorinated biphenyls, tungsten, and vanadium.

The characteristics of each contaminant were listed and included natural and industrial sources and uses, occurrence in drinking water supplies, toxicology, and a list of acceptable treatment methods and removal efficiencies. Each treatment method was considered separately and the descriptions included process theory, process configurations and design, general and specific applications, and process economics. The processes discussed were adsorption, chemical oxidation, coagulation/precipitation, distillation, electrodialysis, ion exchange, radiochemical degradation, reverse osmosis, and ultrafiltration.

In general, the inorganic contaminants can best be treated at present by lime coagulation, possibly followed by a chelation-precipitation/extraction process to polish the effluent. Ion exchange is an ideal method for producing high quality water, particularly at lower feeds. Distillation, electrodialysis, and reverse osmosis hold promise, but more research is required before any firm conclusions can be drawn. Carbon adsorption still appears to be the method of choice for organics removal. The addition of an oxidation or radiochemical treatment step in concert with disinfection, will further improve the water quality from an organic content standpoint.

SECTION I

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Nearly all of the water treatment methods discussed herein are used in one form or another at pilot or full-scale water treatment plants. Many of the specific process variations discussed are still in the experimental stage, but all of the methods are theoretically applicable to water treatment. However, much of the research that has been done on the subject contaminants has related to wastewater treatment. There are certain technical difficulties encountered when applying wastewater treatment data to drinking water treatment because of the different solution concentrations involved. These factors were considered in reaching the conclusions below.

Activated carbon adsorption (or simply carbon adsorption), is commonly employed removing color, odor, taste, and refractory organic compounds from water. Many water treatment plants already use carbon to polish the effluent product. The available data indicates that carbon adsorption is an effective method for removing bis-ethers, chlorinated hydrocarbons, and organic phosphorus insecticides from water. Furthermore, the data indicate that the treatment is more effective on influent waters containing small quantities of contaminants such as are found in potable water sources rather than on wastewaters containing high concentrations. Carbon adsorption may also be used to remove some metals. There is some natural adsorption, but the removal can be greatly enhanced by the addition of an organic chelating agent prior to passage through a carbon column or fine-grain carbon bed. The carbon will readily remove the chelating agent, thereby also removing the complexed metal with it.

Synthetic polymer adsorbents (e.g.,Amberlite XAD-4) have been extensively tested and show some promise. They are not widely used in water treatment plants but have been tested in pilot scale installations. Some tests have yielded higher removal efficiencies for synthetics over carbon for some contaminants. Inorganic adsorbents, such as magnetite, are capable of removing some cations, but since magnetite is a specialty adsorbent, there is the question of general usage. Water treatment plants whose influent contains certain toxic constituents could find a use for synthetic organic resins or inorganic adsorbents, but their use will be limited in the majority of water plants.

Microwave and gamma radiochemical treatment methods are also specialty methods. Furthermore, because of the costs involved, they have to be considered "luxury" methods. For small flows with exotic contaminants and where cost is not a controlling factor, these devices can be useful, but it is doubtful that they will find their way into routine use at most water treatment plants.

Chemical oxidation and ultraviolet irradiation would probably not be worth considering except that these methods are used daily for disinfection. With increasing apprehension over the use of chlorine as a disinfectant, more attention is being focused on the use of ozone and ultraviolet for disinfection. A side benefit of these unit processes is oxidation of refractory organic compounds at slightly increased dosages. No extra equipment, personnel, or maintenance is required and total costs are only marginally higher.

Coagulation/precipitation followed by filtration is probably the most widely used physical chemical water treatment method. Usually lime or alum are used, although activated silica, polycoagulants, ferric chloride, ferrocyanide, sulfides, and carbonates are sometimes used. Coagulation/precipitation followed by filtration methods are relatively effective and low cost, which partially explains their popularity. They do a good job of removing inorganic pollutants present in high concentrations. They also are capable of removing some organic pollutants. For influents with low pollutant concentration levels, however, their removal efficiency drops considerably. Since many drinking water pollutants are hazardous even at low concentrations, other treatment methods may be needed in addition to conventional chemical treatment processes. One possible additional process consists of adding an insoluble chelating polymer, such as chitosan, to the influent water. The flocs formed by the chitosan remove traces of heavy metals and organics by a combination of chelation, enmeshment, and adsorption.

Distillation could conceivably be used to remove most of the inorganic ions. It is commonly used to demineralize many salt or brackish waters. To employ distillation specifically for removing one or more of the subject contaminants, however, would not be economical. Distillation is expensive and other, less-costly alternative methods can do the job sufficiently well. Some organic contaminants are also carried over into the effluent.

Electrodialysis is most applicable to the removal of inorganic ionic substances from water; hence it is generally used in combination with ground water or pretreated surface sources. It is effective in removing dissolved salts, and its efficiency and applicability have increased with advances in membrane and process design technology.

Reverse osmosis is also currently used primarily in desalination operations. It is generally less costly than distillation and can produce a high quality product. If trace toxic substances are involved, there may be some carry-through problem. Furthermore, the presence of significant quantities of organic contaminants may lead to severe membrane fouling and deterioration. Raw water pretreatment, further research, and improved membrane technology should provide higher quality effluents.

Ion exchange demineralization has its greatest current application in small-scale potable water supply and industrial operations. The most common use of ion exchange is for municipal, industrial, domestic, and laboratory water softening. It is particularly suited for brackish water, for pretreating water that is to be completely demineralized, and for certain industrial waters. A large number of water treatment plants use ion exchange for hardness removal and effluent polishing. Ion exchange is potentially capable of meeting all effluent standards for the specific contaminants investigated. There is a problem, however, in that no one ion exchange resin is capable of removing all of the contaminants. The costs of employing several specific ion resins may be prohibitive.

It should be obvious that no single water treatment process will achieve ideal results. To begin with, no one process will work equally well on organics and inorganics. Furthermore, no one process is capable of performing equally well at all concentration ranges for a given contaminant. Consequently, a multi-component treatment process system is desirable to achieve optimum results. For instance, such a system might include pre-chlorination, lime coagulation with chelate addition, followed by carbon adsorption, ion exchange, ozonation and post-chlorination.

Lime coagulation is an effective method for removing antimony (Sb), provided that influent levels are not greater than 80 mg/liter. The solubility of the precipitate is such that there will be a few mg Sb/liter in the effluent. The use of hydrogen sulfide as a precipitant would be more expensive and would not increase removal efficiencies particularly. The ion exchange resins available which can remove antimony generally have not been proven beyond the laboratory test stage. Other possible treatment methods include reverse osmosis, distillation, and electrodialysis. All of these are theoretically capable of producing a satisfactory low antimony content effluent. For smaller plants, ion exchange may be a good choice, once research has provided an effective, long life resin. For larger flows, conventional flocculation, carbon adsorption, and filtration systems may prove most cost effective. Both reverse osmosis and electrodialysis require less space and lower capital expenditures than the latter process facilities.

Beryllium (Be) is effectively treated by ion exchange, reverse osmosis, distillation, or electrodialysis. Reverse osmosis is probably the least efficient process because of the nature of the beryllium ion. Of the other three, ion exchange is a good available unit process and may be a feasible method, except for flows greater than 400 liters/sec where electrodialysis could be competitive. Conventional coagulation, absorption, and filtration has not yet been proven feasible for beryllium removal.

Cobalt (Co) currently is best treated by lime coagulation, although as much as 2 mg/liter may be left in the effluent. The addition of chitosan or a chelate as a polishing agent in connection with coagulation and filtration processes can increase the removal of cobalt and produce a satisfactory potable effluent. Ion exchange, reverse osmosis, distillation, and electrodialysis can also produce a superior quality effluent, but at higher cost. Cobalt concentrations in potable water sources seldom reach levels that require special consideration.

The methods discussed above for cobalt removal are also applicable to molybdenum (Mo), nickel (Ni), and vanadium (V). It should be added that reverse osmosis has been used effectively in pilot plants to treat nickel plating wastes, producing high quality effluents. Again, however, it is a question of space and cost limitations. The same comments also apply to tungsten (W), with the exception that there is no evidence that lime coagulation is an effective removal method for tungsten.

It is questionable whether there exists a need for lithium removal from drinking water. Lithium is not especially toxic, having an LD_{50} of 1.1g/kg body weight. Lithium chloride is used as a salt substitute in low sodium diets and natural concentrations seldom, if ever, exceed about 0.1 mg/liter. If lithium-free water is desired, however, ion exchange, distillation, or electrodialysis could be used to provide it. For an existing treatment plant, ion exchange would be best, keeping in mind that the best resins available for removing lithium would not remove anything else--they could be used only for lithium removal. If a new plant is desired, it might be wise to consider distillation or electrodialysis.

The best presently available method, based on current technology, for treating all organic contaminants is activated carbon adsorption. Treatment efficiencies are consistently high and costs relatively low. The only improvement likely in the foreseeable future is the development of a synthetic adsorption media which may be even more efficient and lower in cost. Adsorption combined with an oxidative disinfectant such as ozone or ultraviolet radiation can remove additional organic contaminants from drinking water. Although other techniques might work for some of the organics, it will be difficult to find a treatment method as all-encompassing as adsorption. Similarly, metal-organic coordination compounds can be removed by adsorption, further enhancing its versatility. See Tables I-1, I-2, I-3, and I-4 for summary information regarding treatment methods.

Recommendations

It should be obvious that a great deal of experimental work is required before any of these conclusions can be taken as final. Many of the recommended removal processes, such as complexation or radiochemical/have only been tested on a laboratory scale. These processes should be tested at least in pilot plant studies before designing a full-scale plant around them.

More laboratory tests should be conducted on the twelve subject contaminants in an effort to determine other, more efficient treatment methods. Further testing should be done on the recommended treatment processes to extend their applicability to other of the subject contaminants. Specific areas requiring research include:

- Coagulation, absorption and filtration processes.
- Distillation as it relates to the subject contaminants.
- Electrodialysis as it relates to the subject contaminants.
- The feasibility of large-scale application of specific-ion exchange resins.
- The toxicity of beryllium and removal processes other than ion exchange, electrodialysis, and distillation.
- Heavy metal chelation and extraction via adsorption.

- The toxicity of lithium to determine if lithium removal is ever necessary.
- The full-scale application of chitosan as a coagulant.
- More efficient treatment methods for tungsten.
- The nature of the reaction product of the chlorinated hydrocarbon and organic phosphorus insecticides with ozone, chlorine, and other oxidizing agents.
- The application of ultrafiltration to removing metal colloids, emulsified organics, and insecticide-oil emulsions.

TABLE I-1

SUMMARY OF TREATMENT METHOD EFFECTIVENESS

Treatment Method	Contaminant	Influent Concentration	Effluent Concentration	Percent Removal	Reference
Adsorption, activated carbon	Isopropyl ether	1,150 mg/liter	200 mg/liter		[illegible]
	Butyl ether	197 mg/liter	~1 mg/liter		[illegible]
	Dichloroisopropyl ether	1,000 mg/liter	~1 mg/liter		[illegible]
	Aldrin	5 mg/liter		85	39
	DDT	5 mg/liter		76	39
	Dieldrin	5 mg/liter		86	39
	Lindane	10 µg/liter	0.05 µg/liter		12
	Parathion	10 mg/liter	0.1-2.5 mg/liter		59
	Malathion	2 mg/liter	0.25 mg/l		39
Adsorption, Amberlite XAD-4	Lindane	40 mg/liter	0.4 mg/liter		[illegible]
	PCBs	*		76	[illegible]
Adsorption, [illegible]	Cobalt			85	[illegible]
	Nickel			87	[illegible]
Chlorination	DDT	2 mg/liter	1.4 mg/liter		[illegible]
	Dieldrin	1.2 mg/liter	0.22 mg/liter		[illegible]

TABLE I-1 (Cont.)
SUMMARY OF TREATMENT METHOD EFFECTIVENESS

Treatment Method	Contaminant	Influent Concentration	Effluent Concentration	Percent Removal	Reference
Permanganate oxidation	Parathion			75	46
	Heptachlor			80	107
Alkaline hydrolysis	Lindane			98.5	107
	DDT			~100	107
Lime coagulation	Antimony			90	37
	Cobalt	12 mg/liter	1.4 mg/liter		57
	Molybdenum			10	37
	Nickel	160 mg/liter	0.20 mg/liter		37
	Nickel	2,955 mg/liter	< 1 mg/liter		44
	DDT	10 µg/liter		98	18
	Endrin	10 µg/liter		35	18
	Dieldrin	10 µg/liter		55	18
Alum coagulation	Nickel	16 mg/liter	11.8 mg/liter		57
	Vanadium	249 mg/liter	1 mg/liter		150
	DDT	10-25 µg/liter	0.1-0.75 µg/liter		39

TABLE I-1 (Cont.)
SUMMARY OF TREATMENT METHOD EFFECTIVENESS

Treatment Method	Contaminant	Influent Concentration	Effluent Concentration	Percent Removal	Reference
Chitosan coagulation	Cobalt	50 mg/liter		62	153
	Molybdenum	2,500 mg/liter	36 mg/liter		153
	Nickel	50 mg/liter	45 mg/liter		153
	Tungsten	500 mg/liter	170 mg/liter		153
Hydrogen sulfide precipitation	Antimony		<2 mg/liter		62, 65
Distillation	Metals			≤ 100	
Electrodialysis	Ionic contaminants			≤ 95	
Ion exchange					
Amberlite CG-400	Antimony	12 µg	~0		89
Zeocarb 50	Beryllium	8.4–10.5 mg		50–100	102
Wofatit KC 50	Cobalt	11–12 mg		~35	98
	Nickel	11–12 mg		~100	98
DEAE cellulose	Molybdenum	0.1–5 mg/liter		≥96	157, 57
	Tungsten	0.004–2 mg/liter		≥98	57

TABLE I-1 (Cont.)

SUMMARY OF TREATMENT METHOD EFFECTIVENESS

Treatment Method	Contaminant	Influent Concentration	Effluent Concentration	Percent Removal	Reference
Ion exchange (Cont.)					
[illegible]	Lithium			~100	101
De-acidite FF	Vanadium	5 mg/liter		96	171
Dowex 1-X8	Vanadium	5.38 µg/liter		97	102
Radiation					
Microwave	Simple ethers			~100	168
Gamma	PCBs	100 µg/liter		95	167
Reverse osmosis	Nickel	93.6 µg/liter		99.6	121, 153
	DDD	532 µg/liter	1.86 µg/liter		128
		500 mg/liter		99	55
	DDT	97 mg/liter	2 mg/liter		174
		500 mg/liter		99	55
	Lindane	500 mg/liter		73	55
		30 mg/liter	8 mg/liter		174
		630 µg/liter	326 µg/liter		128

*Blank spaces indicate that information is not available.

TABLE 1-2

TREATMENT PROCESS STATUS

	Sb	Be	Cd	[illegible]	Hg	Ni	[illegible]	V	Benzidines	PCB	Cl-Hydrocarbons	Org-P Insect.	General Application
Ion Exchange	▒	▒	▒	▒	▒	▒	▒	▒	□	□	▒	□	■
Reverse Osmosis	▤	▤	▤	▤	▤	▧	▤	▤	▤	▤	▒	▤	■
Distillation	▤	▤	▤	▤	▤	▤	▤	▤	□	□	□	□	■
Electrodialysis	▤	▤	▤	▤	▤	▤	▤	▤	□	□	□	□	■
Coagulation/Precipitation	▒	□	■	□	▒	■	▒	▒	□	□	▒	▒	■
Non-Carbon Adsorption	▤	▤	▒	▤	▤	▒	▤	▤	▤	▒	▒	▤	▧
Carbon Adsorption	□	□	□	□	□	□	□	□	▒	▤	▧	▒	■
Radiation(UV)	□	□	□	□	□	□	□	□	▤	▤	▒	▤	■
Radiation(Ozone + gamma)	□	□	□	□	□	□	□	□	▒	▒	▤	▤	▒
Oxidation	□	□	□	□	□	□	□	□	▤	▤	▒	▒	■

■ Full Scale Operational

▧ Pilot Scale Operational Test

▒ Lab Scale Test

▤ Theoretically Applicable, No Data Available

□ Not Applicable

TABLE I-8

PREFERRED TREATMENT METHODS

Treatment Process \ Contaminant	Sb	Be	Co	[illegible]	Mo	Ni	W	V	Bro-mine	PCB	Cl-Hydro-Carbon	Org-P Insect.
Ion Exchange	▨	▨	▨	▨	▨	▨	▨	▨				
Reverse Osmosis	▨	▨	▨		▨	◩	▨	▨			▨	
Distillation	▨	▨	▨	▨	▨	▨	▨	▨				
Electrodialysis	▨	▨	▨	▨	▨	▨	▨	▨				
Coagulation-Precipitation	▩		◩		◩	◩	▨	◩				
Non-carbon Adsorption									▨	▨	▨	▨
Carbon Adsorption									◩	◩	◩	◩
Oxidation									▨	▨	▨	▨
[illegible], [illegible] and [illegible]									▨	▨		

▩ Best available (operational in at least pilot-plant scale)

▨ Best technically feasible (technically proven, may or may not be operational)

◩ Best available is best feasible

☐ Not applicable

TABLE 1-4

TREATMENT METHOD COSTS

Treatment Method	Total Costs[a] (dollars per thousand liters of effluent--1974)	Reference
Adsorption, carbon	0.03 - 0.18	40, 55
Adsorption, synthetic resins	0.04 - 0.32	55
Ozonation	0.007 - 0.1	186
Chlorination	0.001	196
Permanganate oxidation	0.03 - 0.12	55
Lime coagulation	0.035 - 0.13	estimated
Alum coagulation	0.030 - 0.15	55
Chitosan coagulation	0.014 - 0.78	estimated
Hydrogen sulfide precipitation	0.033 - 0.14	estimated
Multistage flash distillation	0.25 - 1.80	89
Combined vapor compression, vertical tube evaporation, multistage flash distillation	0.002 - 0.01	89, 93
Ion exchange--antimony and vanadium	0.062 - 0.88	96
Ion exchange--beryllium	0.008 - 0.5	96
Ion exchange--cobalt and nickel	0.062 - 0.48	96
Ion exchange--lithium	0.062 - 0.48	96
Ion exchange--molybdenum and tungsten	0.06 - 0.4	96
Reverse osmosis	0.12 - 0.88	40, 116, 189, 186
Electrodialysis	0.08 - 0.48	88, 116, 188

[a] These costs represent treatment to a safe, potable effluent. They are summary figures and are not meant to reflect all possible cases. Generally, the conditions used to derive the cost curves in the text were assumed for these costs as well.

SECTION II

INTRODUCTION

With increased water quality consciousness in America, it has become necessary to consider the removal of trace substances from drinking water. Some of these substances are known to have a high acute toxicity if ingested in large quantities, some present problems of chronic toxicity when ingested regularly, some may be carcinogenic; information on the health effects of others is virtually non-existent. Regardless of toxicity, however, if there is any reason to suspect that a substance might have adverse health effects on humans, then it becomes necessary to consider means of removing the substance from drinking water, or at least reducing it to a harmless level.

Recent research has demonstrated possible hazards associated with several substances previously considered harmless. Consequently, there has been a surge of interest in possible treatment methods for removing these substances. This interest has led to considerable research which, although valuable, is scattered, disjointed, and inconsistent. It is extremely difficult to design a treatment plant when data and design information are so scattered and difficult to correlate. As a result, several literature searches have been initiated in an effort to locate, summarize, and evaluate all available data on removing a wide variety of potentially hazardous substances from drinking water.

The hazardous substances considered in this study are antimony, beryllium, cobalt, lithium, molybdenum, nickel, tungsten, vanadium, bis-ethers, polychlorinated biphenyls, chlorinated hydrocarbon insecticides, and organophosphorus insecticides. An effort was made to identify all possible treatment processes and evaluate their efficiencies for removing the subject contaminants. The initial plan was to include all processes for which we had removal information and only those processes. From the first, however, it was evident that this would not be acceptable. For instance, no information was found regarding the use of electrodialysis or distillation to remove any of the subject contaminants. They are included in the report, however, because they will work to some (albeit unknown) extent, and to have left them out would have been to mislead planners. They are workable alternatives and must be considered. On the other hand, a number of processes were left out. For instance, one source detailed a fractional crystallization method for extracting beryllium and lithium from water. The process was deemed to be completely unacceptable from a technical and economic point-of-view, and was not considered a viable alternative. Consequently, it was left out of the final report. Similarly, such waste treatment processes as activated sludge and trickling filters were also left out despite the fact that there was enough data available to indicate that they could remove some of the subject materials. They were not considered to be acceptable as drinking water treatment methods, since drinking water supplies do not contain sufficient nutrients to support the necessary biological growths. Even for the treatment methods that are discussed, much of the information collected relates to the treatment of wastewaters. This is unfortunate because of the difficulty of applying wastewater treatment results to drinking water treatment, but there is very little data relating to the removal of many of the subject contaminants from drinking water supplies. For instance, almost all of the data presented in Table I-1 is derived from wastewater treatment sources. The same treatment methods are used for drinking water treatment, however, and many of the influent concentrations listed in Table I-1 reflect environmental levels.

This report is arranged in two parts. The first (Section III) contains detailed information regarding each of the twelve contaminants. Uses, occurrence, and sources of contamination are described for each substance. Toxicology is discussed in terms of effects and lethal doses. Treatment methods are then listed for each substance with page references to the process descriptions. Where available, removal efficiencies are listed as well.

The second part (Section IV) contains the process descriptions. Each process subsection contains: information on the theory of operation; a description of the working process; some design information, limitations, and constraints; operating conditions; general applicability; specific application to the subject contaminants; and a cost section presenting cost curves, information on the derivation of the curves, and land requirement graphs. All test cost curves are presented in metric units. Appendix figures are presented in English units. The comprehensive bibliography following the report is arranged by category to facilitate further technical review.

SECTION III

CONTAMINANTS

Introduction

This Section contains information on the characteristics of each of the twelve subject contaminants and lists of possible treatment methods for removing them. Each contaminant is treated separately. Information is provided on the industrial uses and routes of entry into drinking water supplies, toxicology (especially as relates to human toxicities), and possibly useful water treatment and removal methods. Each treatment method mentioned is accompanied by the more significant examples of its recorded efficiencies for removing the subject contaminant where such information was available. Other examples are included in Section IV. The page numbers accompanying each treatment method refer to the comprehensive description and analysis of the particular treatment method in question. The first number given is the first page of the discussion of the particular method. Other numbers refer to the specific mention of the subject contaminant in the text. Table III-1 gives a summary of pertinent physical properties of the contaminants.

TABLE II-1

SUMMARY OF [illegible] CONTAMINANT [illegible]

Contaminant	Natural Sources	Industrial Uses	Toxicity (LD50)	Treatment Methods	Notes
Antimony (Sb)	Stibnite Sb₂S₃ (California, Utah, Idaho, Nevada)	Alloys Batteries Paints Glass Medicines	2 mg/kg body weight	Lime coagulation H₂S precipitation Ion exchange Distillation Electrodialysis	
Beryllium (Be)	Beryl Be₃Al₂(SiO₃)₆ (New England, Pennsylvania, Virginia, North Carolina, [illegible], South Dakota, Colorado, California)	Alloys Nuclear reactor parts [illegible] Computer parts	10 mg/kg	Ion exchange Distillation Electrodialysis	More toxic as a vapor than in aqueous solution
[illegible]	None	Solvents Organic synthesis	1 mg/liter – 400 mg/liter (LC50)	Carbon adsorption Microorganism decomposition	Volatile, virtually all boil below 100°C. Insoluble in water
Chlorinated hydrocarbon insecticides	None	Insect control	Variable, but generally high. Endrin – 3 mg/kg DDT – 10 mg/kg Aldrin – 39 mg/kg	Carbon adsorption Coagulation/precipitation Reverse osmosis Chemical oxidation	Refractory, long half-lives, insoluble in water

TABLE B-1 (Cont.)

SUMMARY OF PERTINENT CONTAMINANT PROPERTIES

Contaminant	Natural Sources	Industrial Uses	Toxicity[a] (LD50)	Treatment Methods	Notes
Cobalt (Co)	Cobaltite CoAsS Smaltite (Co,Ni, Fe)As2 (Canada, Idaho)	Alloys Pigments Medicine	150 mg/kg	Magnetic adsorption Coagulation/precipitation Distillation Electrodialysis	An essential nutrient in trace amounts
Lithium (Li)	Lepidolite [illegible] Amblygonite [illegible] Spodumene [illegible] (New England, Calif.)	Alloys Catalysts Organic synthesis	757 mg/kg	Ion exchange Distillation Electrodialysis	Ubiquitous in nature in trace amounts. LiCl used as a salt substitute in low sodium diets
Molybdenum (Mo)	Molybdenite MoS2 (New England, New York, Pennsylvania, Colorado, New Mexico, Washington)	Alloys Glass Ceramics Inks	125 mg/kg	Lime coagulation Ion exchange Calcium precipitation Distillation Electrodialysis	Essential trace element for plants
Nickel (Ni)	Niccolite NiAs Pentlandite (Fe,Ni)9S8 (Canada, New Jersey, Tennessee, Colorado, California)	Alloys Plating Batteries Pigments Organic Synthesis	1600 mg/kg	Reverse osmosis Complexation Ion exchange Distillation Electrodialysis	

TABLE [illegible] (Cont.)

SUMMARY OF PERTINENT CONTAMINANT PROPERTIES

Contaminant	Natural Sources	Industrial Uses	Toxicity[1] (LD50)	Treatment Methods	Notes
Organic phosphorus insecticides	None	Insect control	Variable, but high Parathion — 2 mg/kg Malathion — [illegible] mg/kg	Carbon adsorption Chemical hydrolysis	Biodegradable with short half-lives
Polychlorinated biphenyls	None	Synthesis Insulation Plasticizers Paints	0.5 mg/m^3 (TLV)	Carbon adsorption Gamma irradiation	Insoluble
Tungsten (W)	Wolframite (Fe,Mn)WO$_4$ Scheelite CaWO$_4$ (Connecticut, North Carolina, Missouri, South Dakota, Colorado, Nevada, Arizona, Calif.)	Alloys Lamp filaments	[illegible] mg/kg	Ion exchange Coagulation/precipitation Distillation Electrodialysis	
Vanadium (V)	Carnotite K$_2$(UO$_2$)$_2$(VO$_4$)$_2$·3H$_2$O Vanadinite Pb$_5$(VO$_4$)$_3$Cl (Arizona, New Mexico, Utah, Colorado, Pennsylvania)	Alloys Glassware Dyes Inks Catalysts Pesticides	[illegible] mg/kg	Coagulation/precipitation Ion exchange Distillation Electrodialysis	More toxic as vapor or dust than in solution

Antimony (Sb)

Occurrence.

Antimony is a heavy metal used in the manufacture of bearings, alloys (such as Babbitt metal and hard lead), storage battery grids, pewter, printing type, lead electrodes, rubber, textiles, paint, and glass. Its presence in water supplies can usually be traced to waste discharges from one of these industries. Antimony in solution exists as the Sb^{+3} or Sb^{+5} cation, or as the antimonite (SbO_2^- or $Sb(OH)_6^-$) anion.

Toxicology.

The toxicity of antimony is similar to arsenic's, although less acute. Antimony poisoning can result in dermatitis, keratitis, conjunctivitis, nasal septal ulceration, and liver damage.[64] The industrial threshold limit value (TLV) is 0.5 mg/m^3.[64] Antimony's median lethal dose (LD_{50}) varies from 100 mg/kg as antimony metal to 4,000 mg/kg as $SbCl_3$.[64] A non-official recommended drinking water limit not to be exceeded is 0.1 mg/liter.[55]

Treatment Methods.

Lime Coagulation (Page IV-21, IV-27).* Removal efficiencies of better than 90 percent have been demonstrated.[67]

Hydrogen Sulfide Precipitation (Page IV-21, IV-30). Antimony sulfide has a solubility of less than 2 mg/liter. Removal should be accomplished at least to that limit provided that stoichiometric or better quantities of H_2S are used.[65,66]

Ion Exchange (Page IV-33, IV-42). Laboratory tests with Amberlite CG-400 have demonstrated that at least 15 μg can be removed with 10 g of resin.[67]

Distillation (Page IV-48).

Electrodialysis (Page IV-51).

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* Page number refers to page in Section IV on treatment processes where the particular treatment is discussed.

Beryllium (Be)

Occurrence.

Natural weathering of beryllium-containing minerals can produce beryllium concentrations in water of up to 0.01 µg/liter.[illegible] Higher concentrations are usually the result of industrial waste discharges. Industrial uses and products include nuclear reactor components, solid rocket fuels, filaments in neon and fluorescent tubes, and some alloys. In aqueous solutions the ion normally exists as Be^{+2}.

Toxicology.

Airborne beryllium is extremely toxic. Waterborne beryllium is not nearly as toxic as a rule, except for certain of its salts.[illegible] Exposure to relatively low concentrations of the metal or one of these salts may cause death. Sub-lethal doses may cause dermatitis, chemical conjunctivitis, ulcerations, rickets, blood or bone tumors, kidney stones, and liver damage. The industrial 8-hour TLV is 2 µg/m³ with a 30-minute peak limit of 25 µg/m³.[illegible] Tests on minnows have yielded 96-hour median tolerance limits (TL_m) of 0.15 mg/liter in soft water and 15 mg/liter in hard water.[illegible]

Treatment Methods.

Ion Exchange (Page IV-[illegible], IV-[illegible]). Experiments on solutions containing 4.4 to 10.8 mg Be treated with Dowex 50 have yielded removals of 95-100 percent.[illegible]

Distillation (Page IV-40).

Electrodialysis (Page IV-51).

Bis-Ethers.

Bis-ethers have the structure R-O-R, where R is any organic radical (e.g., ethyl ether, isopropyl ether, phenyl ether, and dichlorethyl ether).

Occurrence.

Bis-ethers do not occur naturally in water, but rather are associated with industrial discharges. Uses vary from one ether to another, but generally include solvents and precursors in organic synthesis. For example, dichloromethyl ether is used as a solvent in textile scouring, isopropyl ether as an anesthetic, and chlormethyl ether as an intermediary in the manufacture of strongly basic anion exchange resins. Concentrations in water are usually quite low, as the various compounds are insoluble. However, bis-ethers can be emulsified under some conditions.

Toxicology.

The bis-ethers are irritants to skin, eyes, and mucous membranes. When ingested in sufficient concentrations they can cause death. Threshold limit values can range from 1 µg/liter for chloromethyl ether to 400 mg/liter for ethyl ether.[5] Chloromethyl ether is a carcinogen.[107]

Treatment Methods.

Carbon Adsorption (Page IV-2, IV-6). In laboratory tests of activated carbon treatment, isopropyl ether concentrations were reduced from 1,023 to 200 mg/liter, butyl ether concentrations from 197 mg/liter to nil, and dichloroisopropyl ether concentrations from 1,008 mg/liter to nil.[165]

Microwave Decomposition (Page IV-77, IV-78). Laboratory tests on simple ethers have achieved reductions approaching 100 percent.[165]

Chlorinated Hydrocarbon Insecticides

The following is a list of chlorinated hydrocarbon insecticides and the drinking water limits proposed for inclusion in the interim primary drinking water regulations.

Insecticide	1974 Limits (mg/liter)
Chlordane	0.003
Endrin	0.0002
Heptachlor	0.0001
Heptachlor Epoxide	0.0001
Lindane	0.004
Methoxychlor	0.1
Toxaphene	0.005

Aldrin, DDT, and Dieldrin are not on the list because their manufacture has been prohibited. However, they may still appear in drinking water as a result of prior applications and current use of previously produced stocks.

Occurrence.

Contamination of water with these insecticides is associated with agricultural runoff, atmospheric fallout, accidental spills, and insecticide manufacturing waste discharges. They are generally applied in aqueous solution, in aqueous slurry, as a powder or dust, or as an oil-borne emulsion. Concentrations are usually quite low, as the various insecticides are virtually insoluble. For example, DDT in United States rivers has been found in concentrations up to 0.72 μ g/liter, Aldrin up to 0.085 μ g/liter, Dieldrin up to 0.17 μ g/liter, chlordane up to 0.075 μ g/liter, Heptachlor up to 0.16 μ g/liter, and Endrin up to 4.33 μ g/liter.[35]

Toxicology.

The chlorinated hydrocarbon insecticides are neurotoxicants. They can enter the body by ingestion, inhalation, or dermal absorption. The nature of the effects and toxicities will vary from individual to individual, ranging from no effects at high intakes to death from moderate intakes. The evidence regarding human toxicity is incomplete and often contradictory. In general, the wisest course is to consider these chemicals as highly toxic and to handle accordingly.

Treatment Methods.

Activated Carbon (Page IV-2, IV-6, IV-7).

- In pilot-plant tests, chlorinated hydrocarbon insecticides at 6.3 µg/liter were reduced to 0.04 to 0.11 µg/liter.[79]
- Laboratory-scale tests on 5 mg/liter solutions yielded removal efficiencies of 76 percent for DDT, 85 percent for Aldrin, and 86 percent for Endrin.[39]
- In laboratory-scale tests, Lindane was reduced from 10 to 1 µg/liter with 29 mg/liter carbon and from 1 to 0.05 µg/liter with 9 mg/liter carbon.[79]
- In laboratory-scale tests, Aldrin and Dieldrin were reduced by 99 percent using 10 g carbon/m³ of water. Insecticide concentrations were not given.[143]

Coagulation/Precipitation (Page IV-21, IV-30).

- In laboratory-scale tests with lime on 10 µg/liter solutions, removal efficiencies of 98 percent for DDT, 55 percent for Dieldrin, 35 percent for Endrin, and less than 10 percent for Lindane were achieved.[79]
- In laboratory tests with alum, DDT was reduced from 10 to 0.2 µg/liter and from 25 to 0.75 µg/liter.[39]
- $KMnO_4$ at 1 mg/liter can oxidize and precipitate sub-mg/liter quantities of Aldrin completely in 15 minutes; at 40 mg/liter, sub-mg/liter quantities of Heptachlor were completely removed in 5 hours. Endrin was not affected.[59]

Reverse Osmosis (Page IV-81, IV-85).

- In laboratory-scale tests using cellulose acetate membranes, Lindane was reduced from 50 to 8 mg/liter and from 500 to 135 mg/liter. DDT was reduced from 910 to less than 5 mg/liter. DDD was reduced from 25 to less than 0.006 µg/liter. Lindane was reduced from 638 to 306 µg/liter.[114,130]
- Other researchers have demonstrated Lindane reductions of 73 percent from 400 mg/liter in raw water and 99 percent reductions of DDT and DDD from 500 mg/liter in raw water.[38]

General Adsorption (Page IV-2, IV-7). In laboratory-scale tests using Amberlite XAD-4, Lindane was reduced from 45 to 0.4 mg/liter. Feeds of 20 mg/liter or less yielded an effluent in which Lindane was undetectable. Similar results were obtained with other insecticides as well.[179]

Oxidation (Page IV-12, IV-14, IV-16). In laboratory-scale water treatment tests, DDT was reduced from 2.0 to 0.14 mg/liter and Dieldrin was reduced from 1.31 to 0.29 mg/liter in 20 minutes using ozone.[163]

Ultra-violet Irradiation (Page IV-77, IV-78). After ultra-violet exposure for one hour, removals of 45 percent (Aldrin), 19 percent (Endrin), and 18 percent (Dieldrin) were achieved. Concentrations were not given.[39]

Ion Exchange (Page IV-60, IV-63). There is some evidence that ion exchange can be used for insecticide removal, but the data are incomplete. See text for particulars.

Ultrafiltration (Page IV-71). Ultrafiltration is capable of virtually complete removal of particulate and oil-emulsified insecticides.[150]

Cobalt (Co)

Occurrence.

Cobalt is commonly used in alloy manufacture, nuclear technology, blue pigments for glass and china, and as a binder in the tungsten carbide tool industry. Cobalt in water can result from waste discharges from these industries or from weathering of cobalt-containing minerals. Natural concentrations can range to as much as 0.019 mg/liter, with an average of 0.002 mg/liter.[33] In solution, it exists primarily as Co^{++}.

Toxicology.

Cobalt is reported to be beneficial or non-toxic in concentrations up to 7 μg/day. In excess it can cause polycythemia and respiratory ailments.[18,174] The TLV is 0.1 mg/m^3.[174] No official or unofficial drinking water limits have been established for cobalt.

Treatment Methods.

Sorption on Magnetite (Page IV-2, IV-7). Removal efficiencies up to 94 percent have been achieved in bench-scale water treatment experiments.[178]

Carbon Adsorption (Page IV-2, IV-7). At a pH of 2.8, the cobalt-APDC* complex can be quantitatively extracted into methylisobutyl ketone (MIBK).[47] Stoichiometric quantities of APDC are required. The APDC complex can be adsorbed onto activated carbon.

Precipitation (Page IV-21, IV-29, IV-30).

- $Ca(OH)_2$ reduced cobalt from 12 to 1.4 mg/liter.[87]
- Chitosan polymer treatment reduced cobalt concentrations by 68 percent in 80 mg/liter Co test solutions.[148]

Ion Exchange (Page IV-58, IV-62). Wofatit MC50 chelating resin has demonstrated virtually complete removal of cobalt from influent solutions containing 11 to 12 mg Co.[98]

Distillation (Page IV-40).

Electrodialysis (Page IV-51).

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* APDC = ammonium pyrrolidine dithiocarbamate.

Lithium (Li)

Occurrence.

Although lithium in water usually results from natural causes, industrial discharges are at times responsible for large or widely fluctuating concentrations. Lithium is used industrially in certain alloys, as a "getter" in vacuum tubes, in lithium-hardened bearing metals, in aircraft fuels, and in the synthesis of catalysts for various chemical industries. Lithium salts are used in porcelain enamels, air conditioning, and multi-purpose greases. In solution, it is found as the Li^+ ion.

Toxicology.

Lithium is not known to be toxic at the concentrations most likely to be encountered. Lithium chloride (LiCl) is used as a salt substitute in low-sodium diets.

Treatment Methods.

Ion Exchange (Page IV-18, IV-42). The ion sieve cation exchange resin ISM-1 is extremely selective for lithium and has demonstrated virtually complete removals at low concentrations.[108]

Distillation (Page IV-40).

Electrodialysis (Page IV-41).

Molybdenum (Mo)

Occurrence.

Molybdenum can occur naturally in drinking water supplies at concentrations up to 90 µg/liter due to weathering of minerals.[33] It can also be found in water as a result of waste discharges from industries related to the manufacture of glassware, ceramics, printing inks, electrical equipment, and certain steel alloys.[15,33] In solution it can exist as the cation Mo^{+3}, Mo^{+4}, or Mo^{+6} or as the molybdate anion (MoO_4^{-2}).

Toxicology.

Molybdenum is mildly toxic to man. In low concentrations it is an essential mineral nutrient acting as a catalyst in the protein xanthine oxidase, a metabolic growth factor.[15] Animal tests have demonstrated that an excess of molybdenum can cause liver and kidney damage.[15] Molybdenum can concentrate in plant tissues up to 15 times the exposure concentration.[33] The TLV's for soluble and insoluble compounds are 5 and 10 mg/liter, respectively.[5] Experiments on minnows have yielded 96-hour LD_{50}'s in soft and hard water of 70 and 370 mg/liter, respectively.[33]

Treatment Methods.

Lime Coagulation (Page IV-21, IV-29). At a pH of 8.9, molybdenum concentrations were reduced by only 10 percent.[97]

Ion Exchange (Page IV-38, IV-43). Several resins have shown a capability of removing 95+ percent of molybdenum from solutions of 0.1 to 5 mg/liter.[97,107]

Precipitation (Page IV-21, IV-30). Chitosan polymer is reported to have reduced molybdenum concentrations from 1500 mg/liter to 56 mg/liter.[105]

Distillation (Page IV-49).

Electrodialysis (Page IV-51).

Nickel (Ni)

Occurrence.

Nickel occurs naturally at concentrations up to 0.073 mg/liter with an average concentration of about 0.005 mg/liter.[93] Wastewater discharges from industries associated with nickel-plating, nickel alloying, storage battery manufacturing, organic hydrogenation, and the manufacture of nickel-chrome resistance wire can contribute to its presence in water sources.[93] In solution, it exists primarily as Ni^{++}.

Toxicology.

Nickel-contaminated water can cause dermatitis in sensitive individuals.[93] Ingestion of large quantities can cause nausea, vomiting, diarrhea, central nervous system depression, and myocardial damage. The airborne TLV is 1 mg/m³.[45] Tests on minnows have yielded 96-hour LC_{50}s of 5 mg/liter in soft water and 43 mg/liter in hard water.[93]

Treatment Methods.

Adsorption on Magnetite (Page IV-2, IV-7). Laboratory tests have demonstrated up to 98 percent removal of nickel.[148]

Reverse Osmosis (Page IV-21, IV-30). Tests on nickel plating wastes with a nickel concentration of 62.8 g/liter have demonstrated up to 99.6 percent reduction.[121,153]

Precipitation/Coagulation (Page IV-21, IV-29, IV-30).

- $Al_2(SO_4)_3$ treatment can reduce wastewater nickel concentrations from 16 to 11.70 mg/liter.[87]
- $Ca(OH)_2$ dosages can reduce wastewater nickel concentrations from 16 to 6 mg/liter.[87]
- Lime coagulation and precipitation can reduce nickel concentrations from 160 to 0.08 mg/liter.[87]
- Lime coagulation has been employed to reduce nickel concentrations from 2933 to less than 1 mg/liter.[44]
- Chitosan polymer can reduce nickel concentrations from 80 to 45 mg/liter.[152]

Ion Exchange (Page IV-38, IV-42). Wofatit MC50 chelating resin has demonstrated virtually complete removal of nickel from solutions containing 11 to 12 mg Ni.[96]

Distillation (Page IV-40).

Electrodialysis (Page IV-21).

Organic Phosphorus Insecticides

Occurrence.

Organophosphorus insecticides are short-lived, biodegradable, and highly toxic. The more common ones include Demeton, Malathion, and Parathion. Standards have been established for those whose half-lives in water exceed eight weeks, such as Azodrin (0.003 mg/liter), Dichlorvos (0.01 mg/liter), Dimethoate (0.002 mg/liter), and Ethion (0.02 mg/liter). Like the chlorinated hydrocarbons, they do not occur naturally in water, but are associated with wastes from manufacturing and agricultural uses. Concentrations of several μg/liter have been found.[9]

Toxicology.

The organophosphorus insecticides have a high acute mammalian toxicity. They are cholinesterase inhibitors and consequently can cause severe malfunctions of neurotransmitter mechanisms. Parathion and its derivatives are the most toxic organic phosphorus insecticides; Malathion is about 0.01 as toxic.[15]

Treatment Methods.

Activated Carbon (Page IV-2, IV-7).

- In laboratory-scale tests, Parathion was reduced from 10 to 0.6 mg/liter and Malathion from 8 to 0.24 mg/liter. Powdered carbon was used at 10 mg/liter dosages.[9]

- In laboratory-scale tests, Parathion was reduced from 10 to 0.8 mg/liter using 5 mg/liter powdered carbon, from 10 to 0.1 mg/liter using 20 mg/liter powdered carbon, and from 11.4 to 0.05 μg/liter using dual granulated carbon columns.[9]

Chemical Hydrolysis (Page IV-16). One hundred percent reduction is possible using 0.25 percent hypochlorite.[9]

Polychlorinated Biphenyls (PCB's)

Occurrence.

These organic compounds do not occur naturally in water, but rather are associated with waste disposal and accidental spills. Recent American regulations have restricted their use to closed system electrical applications as insulation.[5,81] Previously, they were often used in the manufacture of plasticizers, flame retardants, synthetic rubber, floor tile, ink, and paints.[94] Aqueous concentrations are usually quite low, as the various biphenyls are insoluble. Most of the PCB's produced in this country are produced by Monsanto and are identified by the trade name Aroclor.

Toxicology.

The toxicity of the PCB's increases with increasing chlorine content.[88] The human organs particularly affected include the liver and kidneys.[94] The LD_{50} for PCB's ranges from 500 to 4500 mg/kg.[197]

Treatment Methods.

General Adsorption (Page IV-6, IV-7).

- In laboratory tests using ion exchange, Amberlite XAD-4 treatment removed up to 76 percent. Concentrations were not reported.[178]
- Several clay minerals have demonstrated PCB removal capability in laboratory tests: illite 60 percent, montmorillonite 40 percent, and kaolinite 40 percent.[16]

Gamma Irradiation (Page IV-77, IV-78). Tests on 100 μg/liter solutions of PCB's yielded treatment removal efficiencies as high as 98 percent, depending on the dose, pH, and presence or absence of oxygen.[161]

Tungsten (W)

Occurrence.

The presence of tungsten in water can be attributed primarily to industrial discharge. Tungsten is commonly used for incandescent lamp filaments and electron tubes, in electronic communication apparatus, and as a toughener in the manufacture of steel. It exists primarily as the tungstate anion ($WO_4^=$) in aqueous solution.

Toxicology.

Little data is available on the toxicity of tungsten. In experiments on chickens, ingested tungsten prompted the excretion of molybdenum, the loss of which adversely affected their growth metabolism.[14] The LD_{50} for soluble tungsten is 1190 mg/kg.[107]

Treatment Method.

Ion Exchange (Page IV-58, IV-62). DEAE cellulose is capable of reducing tungsten concentrations of 0.004 to 5 mg/liter by 98 or more percent.[97]

Precipitation (Page IV-21, IV-30). Chitosan polymer has reduced tungsten concentrations from 500 to 170 mg/liter in laboratory tests.[148]

Distillation (Page IV-40).

Electrodialysis (Page IV-51).

Vanadium (V)

Occurrence.

Vanadium in water is usually associated with industrial discharge. It can occur naturally in concentrations up to 13 mg/liter, but is usually in significantly smaller quantities.[illegible] It is used in the production of rust-resistant steel and in glassware, dyes, inks, paints, varnish dryers, alloys, pesticides, and fuel oils.[illegible] Vanadium pentoxide (V_2O_5) is used as a catalyst in the manufacture of H_2SO_4.[illegible] In solution, it may be found as V^{+3}, V^{+4}, metavanadate (VO_3^-), VO_4^{-3}, or $V_2O_7^{-4}$.

Toxicology.

There is no strong evidence that vanadium is carcinogenic to man or animal.[98] It inhibits the synthesis of cholesterol.[illegible] When ingested it can cause gastric intestinal disturbances; inhibit the enzyme cholinesterase;[illegible] cause a decrease in serum albumin; and cause fatty degeneration, cirrhosis of the liver, kidney damage, anemia, and muscular atrophy.[98] The TLV for V_2O_5 dust is 0.5 μg/m³, and for its fumes is 0.05 mg/m³.[illegible] The 96-hour TLm for vanadium as vanadyl sulfate is 4.8 mg/liter in soft water, and 50 mg/liter in hard water.[illegible] The 96-hour TLm for V_2O_5 is 13 mg/liter in soft water, and 55 mg/liter in hard water.[illegible]

Treatment Methods.

Coagulation/Precipitation (Page IV-21, IV-30).

- Coagulation with iron or aluminum salts is capable of reducing concentrations from 340 to 1 mg/liter.[140]
- Chitosan polymer reportedly precipitates vanadium quite effectively. Numerical data were not found, however.

Ion Exchange (Page IV-58, IV-63). De-acidite FF can reduce vanadium in solutions containing up to 8 mg by 98 percent.[107] Five grams of Dowex 1-X8 can produce a 97 percent vanadium-free effluent from 3 liters of sea water containing 0.08 μg vanadium/liter.[99]

Distillation (Page IV-40).

Electrodialysis (Page IV-51).

SECTION IV
TREATMENT PROCESSES

Introduction

This Section contains detailed descriptions of the water treatment methods referenced in Section III: adsorption, chemical oxidation, coagulation/precipitation, distillation, electrodialysis, ion exchange, radiochemical degradation, reverse osmosis, and ultrafiltration. Each treatment method sub-section includes process theory, process description, limitations and constraints, applications, and specific applications for the twelve subject contaminants. Each sub-section presents capital, operation and maintenance, and total cost estimate curves. Information describing the references used to formulate the cost curves can be found in the Appendix. Land requirement curves are also presented.

Adsorption

Process Description and Theory.

Adsorption is a surface phenomenon involving the accumulation of substances at a surface or interface between one phase and another. The process can occur at the interface between any two phases but, in the case under consideration, only the liquid-solid interface will be discussed.

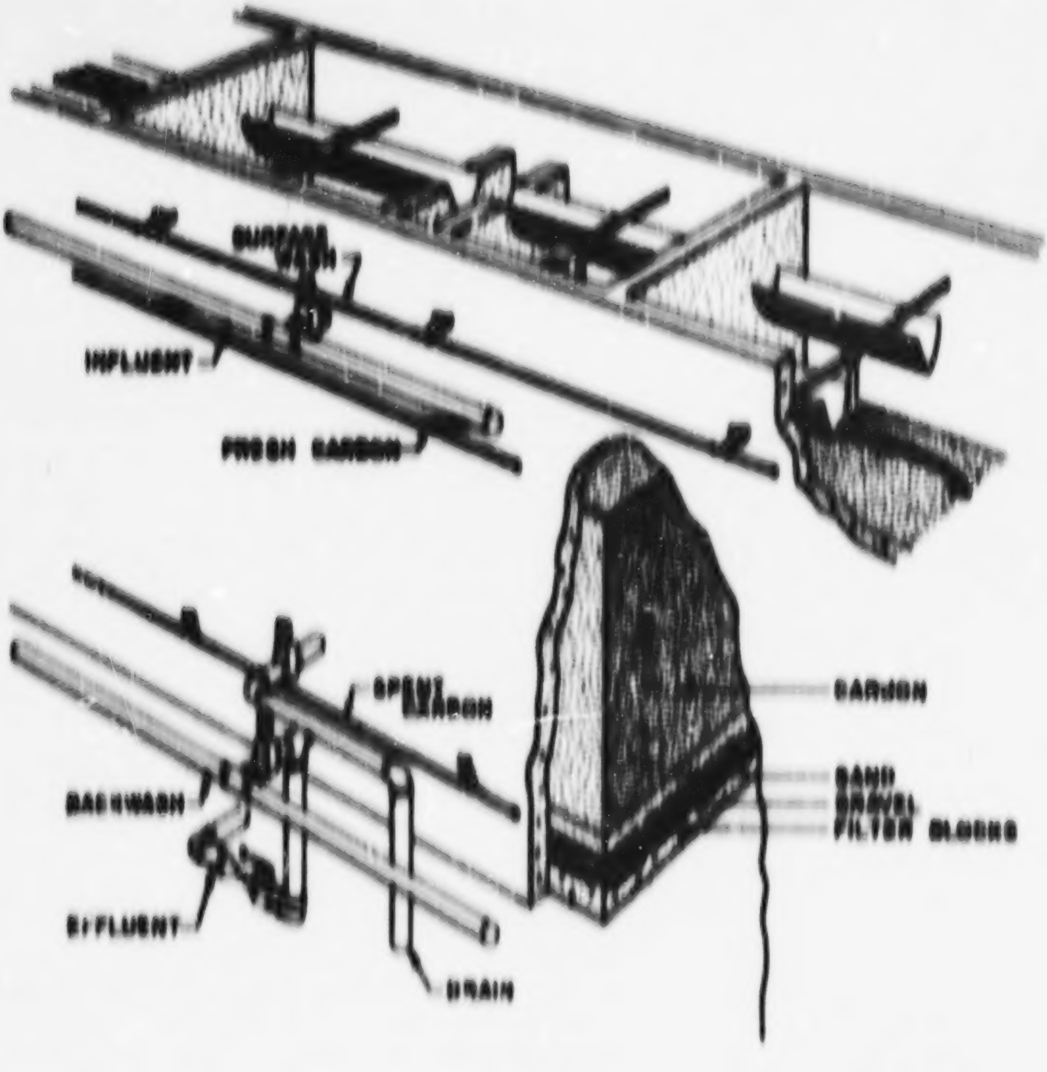
Adsorption from solution onto a solid generally results from one of two driving forces (or a combination, as is the case with most water and wastewater treatment systems). These driving forces may result from a lyophobic (solvent-disliking) solute in regards to the solvent, or from a solute with a high affinity for the solid. The intensity of the first force is related to the solubility of the dissolved substance. The less soluble or more hydrophobic a substance is, the more likely it is to move toward an interface and be adsorbed. The second driving force results from a specific affinity of the solute for the solid. This affinity may be one of three types of surface phenomena: electrical attraction, van der Waals' attraction, or chemical attraction. The first falls under the heading of ion exchange and as such is discussed elsewhere. Adsorption as a result of van der Waals' forces is generally termed "physical" adsorption. Chemical adsorption or "chemisorption" describes the situation where the adsorbate undergoes chemical interaction with the adsorbent.

There are basically two modes of operation--batch-type contact and column-type continuous flow. In a batch operation, a quantity of the adsorbent (powdered, granular, pelletized, etc.) is added to a specific volume of water to be treated. The solution is mixed and allowed to remain in contact for a predetermined time. The adsorbent is then filtered out, leaving a cleaner effluent. The exhausted adsorbent can be discarded or regenerated. The influent in column operations (see Figures IV-1 and IV-2) passes through a fixed column of adsorbent, producing a cleaner effluent. When the adsorbent can no longer remove the contaminants, the exhausted column is withdrawn and either discarded or regenerated. Fixed-bed adsorption systems can be operated in series or parallel (Figure IV-3).

Moving-bed operations are variations on the column-type configuration. In a moving bed, the water flow is directed upward through the bottom of the adsorber and clean water is drawn off at the top. The system is designed to remove slugs and exhausted adsorbent from the bottom while fresh adsorbent is added at the top.

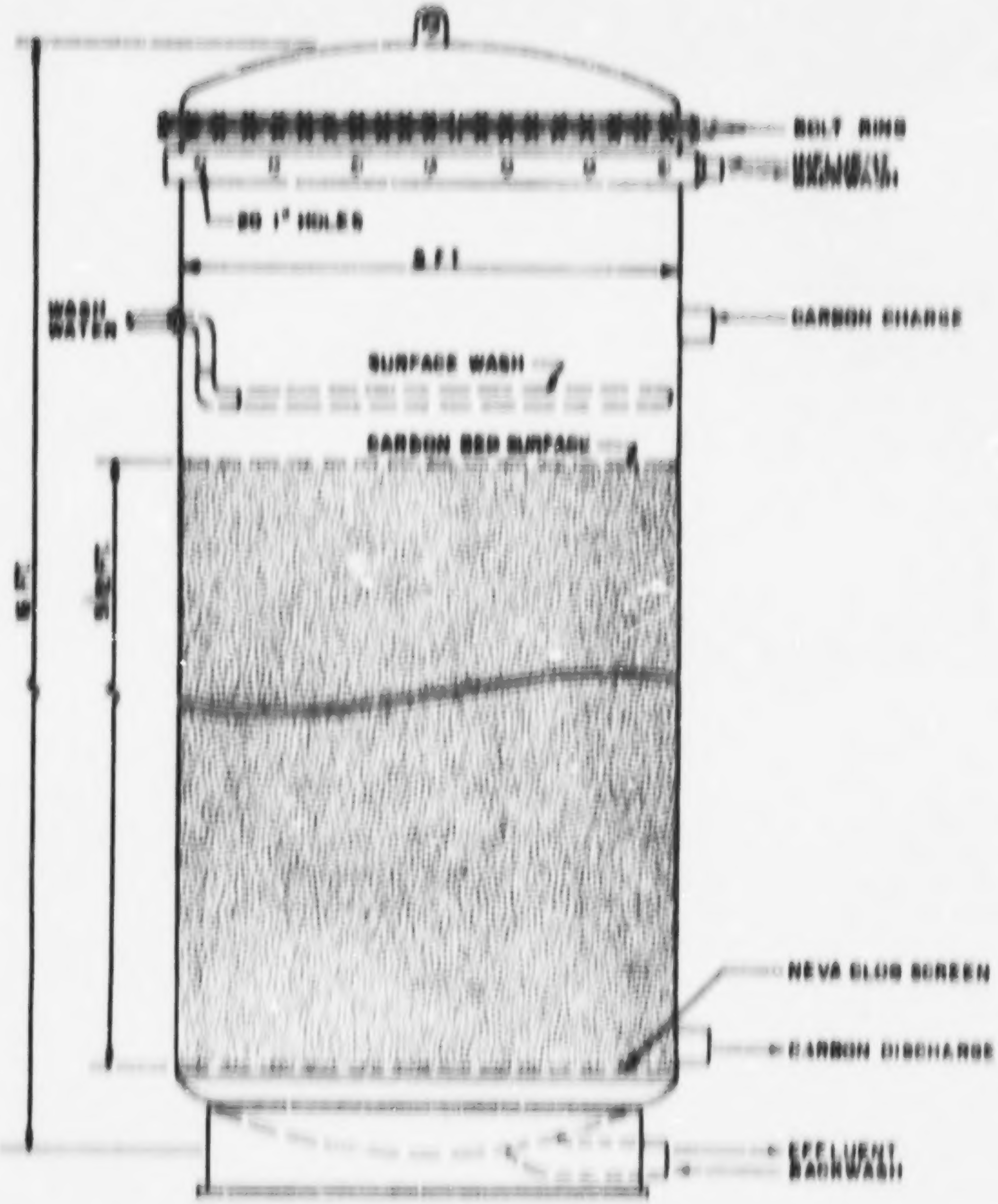
The most frequently used absorbents of the several available are activated carbon, powdered or granular charcoal, and carbon. Generally speaking, granular carbon is used in column-type operations and powdered carbon in batch-type units.

Column-type carbon units are usually operated at 1 to 2 liters/sec/m^2 with column dimen-


SURFACE WASH
INFLUENT
FRESH CARBON
SPENT CARBON
BACKWASH
EFFLUENT
DRAIN
CARBON
SAND
GRAVEL
FILTER BLOCKS

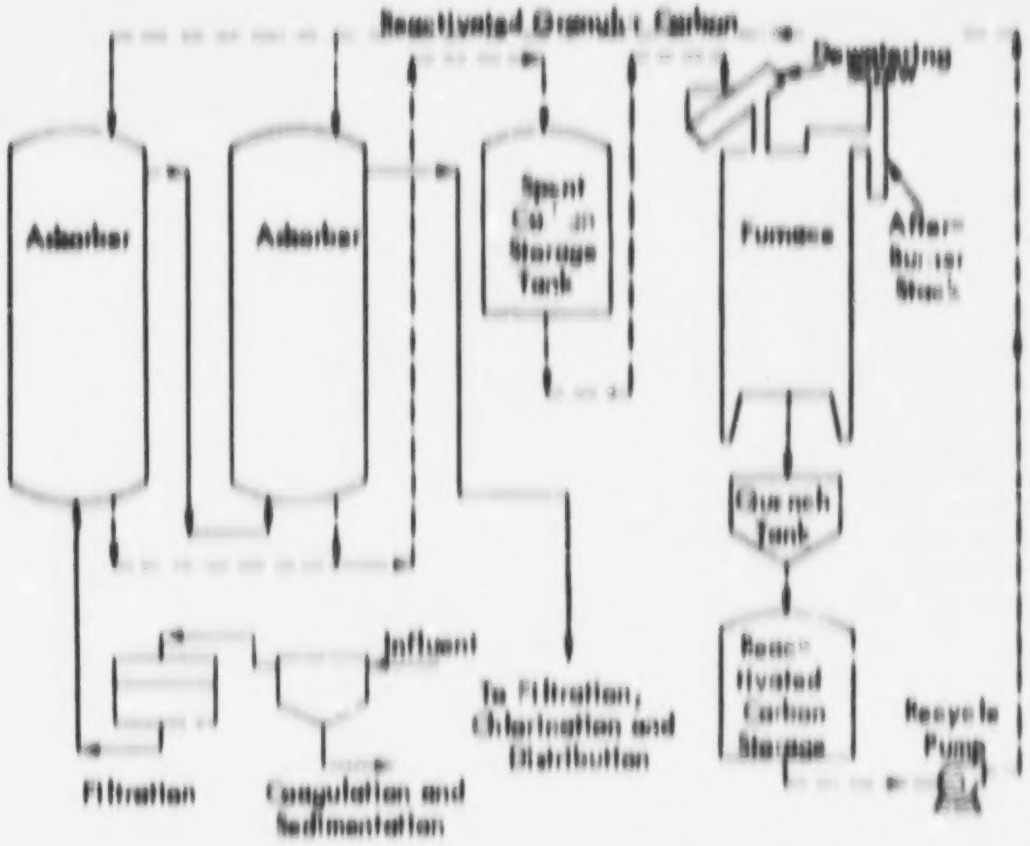
Source: 173

FIGURE IV-1
TYPICAL ACTIVATED CARBON
ADSORPTION BED


BOLT RING
INFLUENT
BACKWASH
20 1" HOLES
8 FT
WASH WATER
CARBON CHARGE
SURFACE WASH
CARBON BED SURFACE
NEVA CLOG SCREEN
CARBON DISCHARGE
EFFLUENT
BACKWASH

Source: 193.

FIGURE IV-2
TYPICAL ACTIVATED CARBON
ADSORPTION COLUMN
(LAKE TAHOE)


Reactivated Granular Carbon
Dewatering Screw
Adsorber
Adsorber
Spent Carbon Storage Tank
Furnace
After-Burner Stack
Quench Tank
Reactivated Carbon Storage
Recycle Pump
Influent
To Filtration, Chlorination and Distribution
Filtration
Coagulation and Sedimentation

Source: 55.

FIGURE IV-3
CARBON ADSORPTION:
FIXED BED IN SERIES

sions of 3 to 9 m deep and 1.2 to 6 m in diameter. Contact time averages about one to two hours. When powdered activated carbon is being used, the carbon dosage is usually kept at 50 to 3,000 mg/liter of water. The residence time is 2 to 3 hours if three consecutive adsorption tanks are used, 48 to 120 hours if there is only one tank.

Using activated carbon, pretreatment is necessary if the suspended solids concentration in the water exceeds 50 mg/liter. Chemical clarification is usually least expensive, although filters are more reliable. The activated carbon becomes exhausted after a certain period. It can be reactivated by dewatering, then heating to 816 to 927 C until the adsorbed impurities are oxidized and vaporized.

Other adsorbents are usually applied in a similar fashion. Among the more common types are clays, silica, zeolites, magnetite, and polymeric material. Clay's natural adsorbency has been put to use in water and wastewater treatment. Clay is not particularly easy to work with, but it is cheap and can be easily disposed of by landfilling. Silica is another good natural adsorbent, but purified silica is expensive and its use has largely been limited to laboratory separations. Zeolites and magnetite lie about mid-way between ion exchange and adsorption. They are used most commonly for water softening and are regenerated chemically. A number of synthetic organic polymers, such as polyurethane and Amberlite, have found application as adsorbents. They are easily regenerated chemically and virtually indestructible under normal operating conditions.

Application.

Activated carbon, probably the most useful method for removing organic compounds from water, is commonly used for removing humic taste and odor compounds from drinking water and for removing refractory organics from sewage. Enough information is available to show that it could be used to treat all of the organic subject contaminants.

Laboratory tests on ethers have shown activated carbon capable of reducing isopropyl ether concentrations from 1023 to 203 mg/liter, butyl ether concentrations from 197 mg/liter to nil, and dichloroisopropyl ether concentrations from 1008 mg/liter to nil.[168] The research indicated that higher molecular weight ethers are more readily adsorbed than lower weight ethers. The lower the solubility of the ether, the higher the adsorption. Higher pH tends to increase the capacity of the carbon.[168]

Investigations of Endrin and Dieldrin with initial concentrations in the range of 0.5 to 10 μ g/liter have found that the pesticides could be reduced to 0.25 μ g/liter with powdered activated carbon dosages of 30 to 60 mg/liter. Sigworth found that over 99 percent of Chlordane with a 50 mg/liter initial concentration was removed by a 10 mg/liter carbon dosage.[28] Whitehouse investigated Aldrin and Dieldrin with concentrations of 0.0066 and 0.0044 mg/liter, respectively, and showed that over 90 percent removal could be obtained after one hour and a carbon dosage of 100 mg/liter for Aldrin and 200 mg/liter for Dieldrin.[76] Sigworth studied DDT and Lindane with initial concentrations of 5 mg/liter and 25 mg/liter, respectively.[25] He concluded that 10 mg/liter carbon dosage in the treatment plant could accomplish 90 percent removal of most pesticides. Adsorption by granular carbon has been considered one of the most effective methods of removing organic phosphorus insecticides. Robeck found that Parathion concentration in water was reduced from 11.4 to 0.05 mg/liter by passage through two carbon columns.[66] The necessary carbon dosage and the associated degree of removal for methyl Parathion, Demeton, and Guthion should be in the same range as those for Parathion. Huang found that 10 mg/liter carbon could reduce Parathion from 10 to 0.1 μg/liter and 126 mg/liter carbon could reduce Endrin from 10 μg/liter to 0.1 μg/liter.[16]

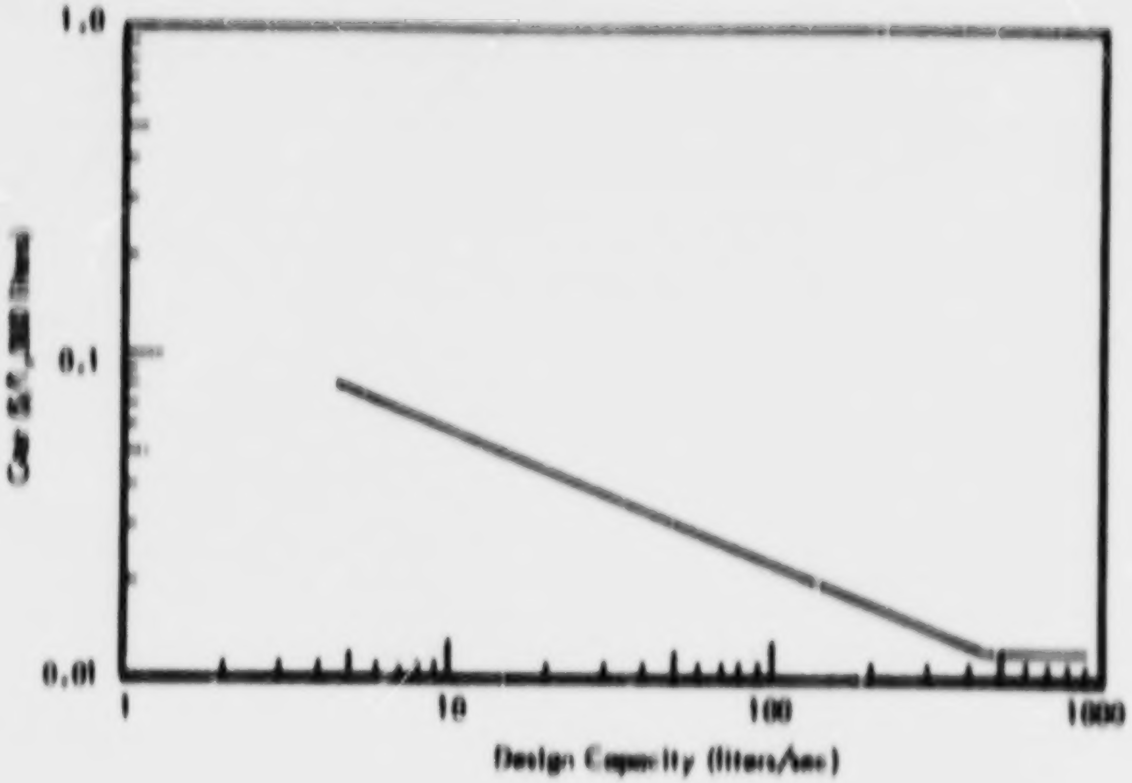
Although no data were found, activated carbon should also be able to remove the heavy metals. There is some removal of the ions, but removal efficiencies can be increased to nearly 100 percent by adding an organic chelating agent (such as dithizone, oxime, or EDTA).[77] The carbon removes the complex by adsorbing the organic agent, bringing the metal with it.

There are other adsorbents capable of removing pesticides. Musty investigated the use of the synthetic polymer Amberlite XAD-4 for the removal of various insecticides.[175] The pesticides examined included α-BHC, Lindane, β-BHC, Aldrin, and Dieldrin in tap water at initial concentrations of 1 μg/liter each. He found consistent removals of better than 60 percent.

Voznesenskaya investigated the use of crushed magnetite for the removal of nickel and cobalt.[176] Crushed natural magnetite (diameter 0.4 to 0.6 mm) was used in 60 cm deep beds. Removal efficiencies for cobalt and nickel were 94 and 86 percent, respectively. Concentration data were not given.

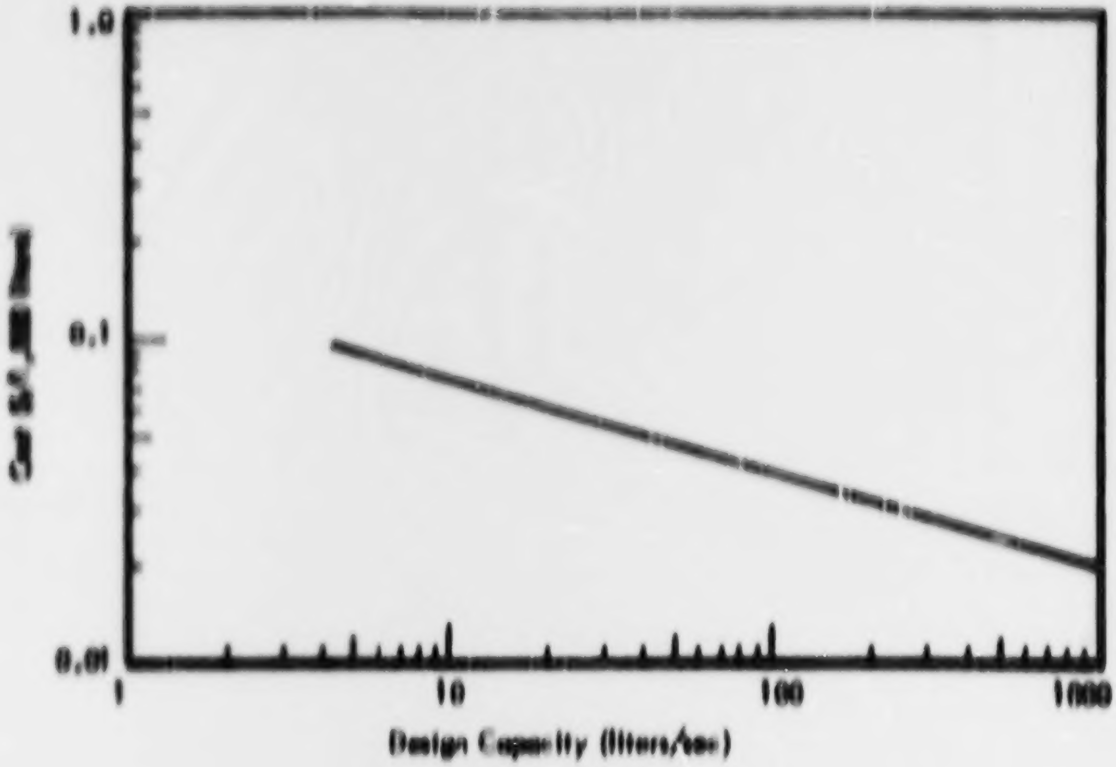
Activated Carbon Costs.

Costs were estimated over a plant size range of 1 to 1,000 liters/sec. Capital costs were amortized at 7 percent over a twenty year period. Capital costs decline until about 450 liters/sec, where adding duplicate units causes the curve to level. Operation and maintenance costs included overhead (40 percent of the costs). Carbon costs were estimated to be $0.66/kg. A powdered carbon dosage rate of 100-250 mg/liter was used with a recovery rate of 85 percent. For granular carbon, a 5 percent loss upon reactivation was assumed. In determining frequency of regeneration, a hypothetical water concentration of 750 mg/liter was assumed. This includes all possible contamination which might be removed by carbon and not just the subject contaminants. Electrical power was estimated at $0.02 per kwhr. Estimates of capital cost (Figure IV-4), operation and maintenance cost (Figure IV-5), total cost (Figure IV-6), and land requirements (Figure IV-7) are presented. Land requirements were calculated based on in-house information and manufacturers' claims.



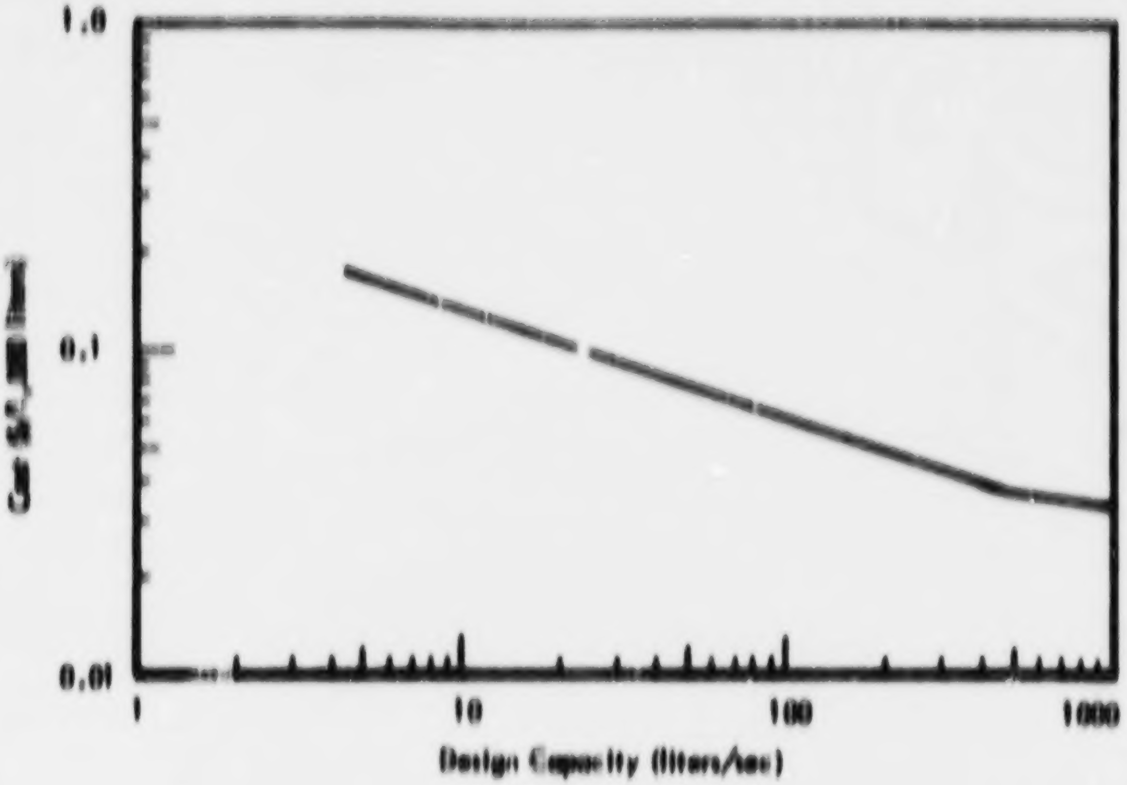
Source: See Figure A-1.

FIGURE IV-4
ACTIVATED CARBON ADSORPTION:
CAPITAL COST
1974



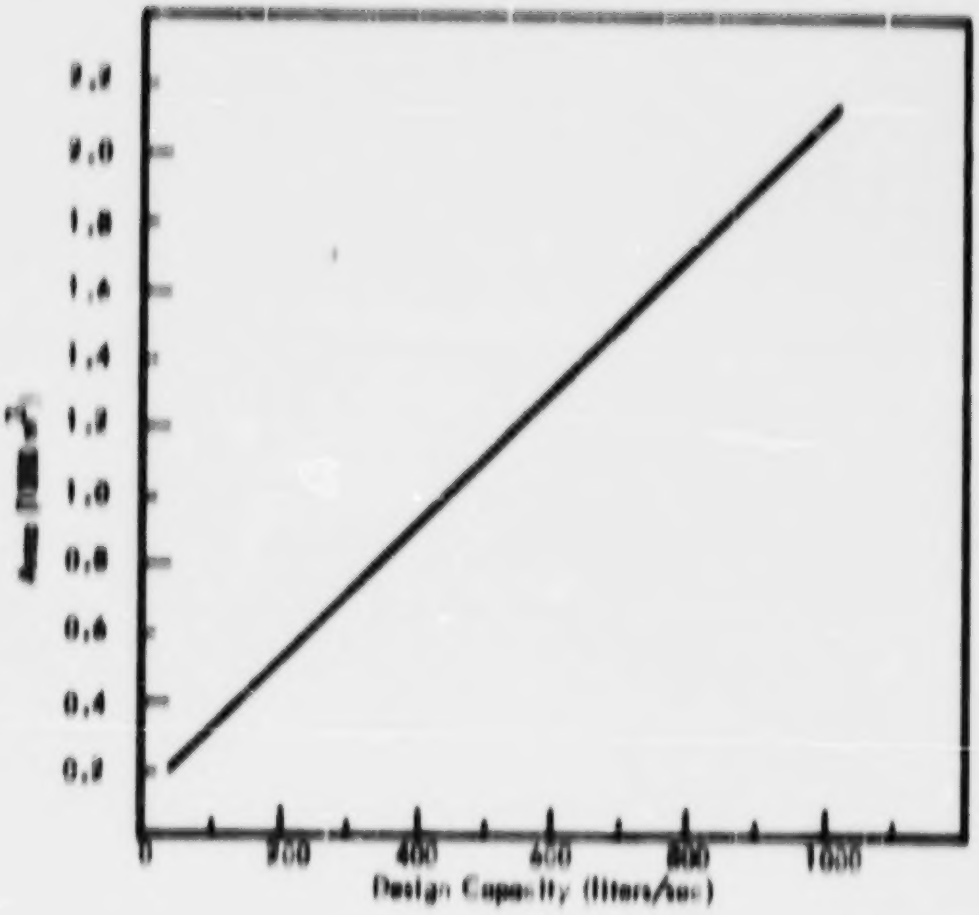
Source: See Figure A-8.

FIGURE IV-8
ACTIVATED CARBON ADSORPTION:
OPERATION AND MAINTENANCE COSTS
1974



Source: See Figure A-3.

FIGURE IV-6
ACTIVATED CARBON ADSORPTION:
TOTAL COST
1974



Source: 198.

FIGURE IV-7
ACTIVATED CARBON ADSORPTION:
LAND REQUIREMENTS

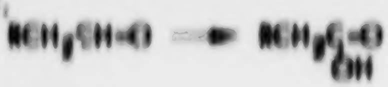
Chemical Oxidation

Process Description and Theory.

Oxidation, a chemical process involving some change in the nature of the chemical compounds involved, results from: withdrawal of hydrogen, addition of oxygen, or withdrawal of electron(s).[10] The first type of reaction can be illustrated by the oxidation of an alcohol to an aldehyde.

$$RCH_2CH{-}OH \longrightarrow RCH_2CHO$$

The second type of reaction can be illustrated by the oxidation of an aldehyde to an organic acid.



$$RCH_2CH{=}O \longrightarrow RCH_2\underset{OH}{C}{=}O$$

The third type of reaction involves electron transfer from the substrate to the oxidizing agent.

$$-\overset{|}{\underset{|}{C}}=\overset{|}{\underset{|}{C}}- \; + \; Cu^{(+2)} \longrightarrow \rangle C = C \langle \; + \; Cu^{(+1)} \; + \; 1/2H_2$$

For certain simple inorganic reactions, oxidation is equivalent to a loss of electrons. In general, oxidation (like reduction) refers to the change of oxidation state or oxidation number. When a compound contains an atom which undergoes an increase in oxidation number, the compound is said to be oxidized.

Oxidation is used as a water treatment to convert undesirable chemical and biological species into species which are neither harmful nor otherwise objectionable. Most frequently it is neither necessary nor practical to carry the oxidation process to absolute completion, as compounds of much lower toxicity are formed as intermediate oxidation products. In general, chemical oxidation for water treatment includes the oxidation of inorganic substances such as Mn^{+2} (to $MnO_2(s)$), S^{-2} (to SO_4^{-2}), SO_3^{-2} (to SO_4^{-2}), etc., and organic substances such as phenols, amines, humic acids, bacteria, and algae.

The four major oxidation agents generally used are: air, ozone, chlorine, and permanganate. Aeration is used to accomplish several purposes other than oxidation, such as stripping of volatile gases and organics. It is used to oxidize divalent iron and manganese and certain taste and odor imparting organic compounds. The major disadvantage of aeration is that the oxidation proceeds more slowly than in other oxidation methods. There are several ways in which aeration can be accomplished. The most common is air diffusion, in which compressed air is bubbled through the water. A similar process involves the spraying of water into the air. In a third method--gravity aeration--the water is allowed to fall over a series of steps and baffles.

Ozone is useful for phenol and cyanide oxidation, iron and manganese removal, disinfection, and taste and odor removal. For ozonation of water, ozone must be manufactured at the treatment site. Ozone is unstable, spontaneously decomposing to oxygen, and consequently cannot be stored for any length of time. Clean, dry air or oxygen is passed through an electrical discharge to generate the ozone. The gaseous ozone is then mixed with the water in a contact chamber or ozone tower.

The disinfection of relatively clean water requires 1 to 2 mg ozone/liter.[190] The efficiency of ozone absorption from air depends on the time of exposure, the effective interface, and the concentration differential. The advantages of using ozone as an oxidant include its rapid rate of reaction, the fact that it imparts no taste or odor to the water, and the fact that it adds no dissolved solids which must be removed later. Ozone's disadvantages include its relatively high cost and that it must be generated on site and used immediately.

Chlorine, the most common method of destroying disease-producing organisms found in drinking water, also improves coagulation and odor control. The advantage of using chlorine is based on its relatively low cost and its oxidizing power. Chlorine gas is highly irritating and must be handled with care. Below 9.6°C, chlorine combines with water to form chlorine hydrate (chlorine ice) which obstructs feeding equipment. If phenols contaminate the water, chlorine disinfection can cause the formation of chlorophenols, which impart unpleasant tastes and odors. There is some evidence that chlorine reacts with industrial organic wastes to produce toxic carcinogens.

Chlorine is available as a relatively pure liquid or in solid compounds. The chlorine compounds which have been used for water-treatment are chlorinated lime ($CaCl(OCl)$), calcium hypochlorite ($Ca(OCl)_2$), sodium hypochlorite ($NaOCl$), and chlorine dioxide (ClO_2). For relatively large-scale water treatment, liquid chlorine is much less expensive than solid. Chlorine gas is toxic and the chlorine containers must be handled with utmost care.

There are two ways to feed the chlorine gas: direct feed and solution feed. In direct feed, chlorine gas is fed directly into the water by means of a control and measuring device known as a chlorinator. In this process, particular care must be taken to provide suitable diffusion of the gas at adequate submersion depth to prevent the loss of free chlorine. Usually, it is submerged at least four feet. In solution feed, chlorine gas is dissolved under controled conditions in a small flow of water that is passed through a gas-flow regulating device. This concentrated solution of chlorine is then added to the water to be treated. Solid chlorine compounds are generally dissolved in a small quantity of water before they go to the feeding point. These solutions or slurries are then added to the water.

Potassium permanganate ($KMnO_4$) has been used as a water treatment to remove iron and manganese as the oxides and organic compounds by oxidation. Organic oxidation products are enmeshed in the resulting MnO_2 precipitate. Potassium permanganate is a powerful oxidizing agent, does not impart tastes or odors to the water, is relatively safe and easy to handle, and can be fed either as a solid or as an aqueous solution. Solids are fed directly into the raw water in large mixing chambers. Mechanical mixing is necessary to ensure complete mixing and dispersal of the permanganate. Solution permanganate is fed from a chemical tank in which the solution is agitated constantly to insure mixing. The feed rate is usually proportional to the flow rate of the raw water.

Application.

Of our subject contaminants, the organics are more susceptible to oxidation than the inorganics. Theoretically, some of the transition metals could be oxidized to the oxides (which are insoluble), but, in practice, this is usually kinetically unfavorable. This discussion of the specific applications of oxidation will consequently be limited to the organic compounds.

Most of the available information concerns the oxidation of insecticides. Chlorination is not particularly effective in oxidizing chlorinated hydrocarbons.[19,55,109] Furthermore, there is a distinct possibility that the chlorine and insecticides will react to form new compounds which may be more toxic than the original chlorinated hydrocarbons.[109] Consequently, the use of chlorine is not recommended for treating chlorinated hydrocarbons.

Data on the use of potassium permanganate as the oxidant are contradictory. It would seem that different pesticides are affected differently. One researcher reported that $KMnO_4$ was ineffective in removing Endrin and Dieldrin but was capable of 80 + percent removal of Aldrin and Heptachlor under a wide variety of conditions and with short contact times.[59] A pilot study demonstrated no effect on Lindane, Endrin, Dieldrin, or DDT, but 75 percent removal of Parathion.[55] Another researcher found that Lindane and Endrin were not affected, DDT was partially reduced, and Heptachlor was 80 percent removed.[107] Permanganate applications seldom exceed 5 mg/liter.[55]

Ozone is capable of reducing Dieldrin by 80 percent and reducing Endrin from 10 mg/liter to 5 mg/liter at 10 mg/liter O_3.[59] Another study showed 75 percent removal of Lindane and virtually complete removal of Dieldrin and Aldrin.[55] See Table IV-1 for the results of a third study.

Aeration is generally ineffective, except on Aldrin and possibly Dieldrin.[55,59] Removals of Aldrin can be as high as 85 percent.[59] Hydrogen peroxide is ineffective in removing Aldrin or Lindane from solution. Other oxidizing agents, such as persulfate, have only limited applicability, usually under very special conditions, and for only one or two insecticides.[55,59]

A similar process, hydrolysis, involves the destruction of organic chemicals under strongly acidic or basic conditions. This is usually accomplished using typical pH adjusting chemicals, such as H_2SO_4, HCl, NaOH, and NH_4OH. A further treatment step is required to readjust the pH.

Whitehouse reported that below a pH value of 5 the concentration of Aldrin and Dieldrin in water rapidly decreased due to hydrolysis.[76] Endrin has also been reported

TABLE IV-1
EFFECT OF OZONATION ON
CHLORINATED HYDROCARBON INSECTICIDES

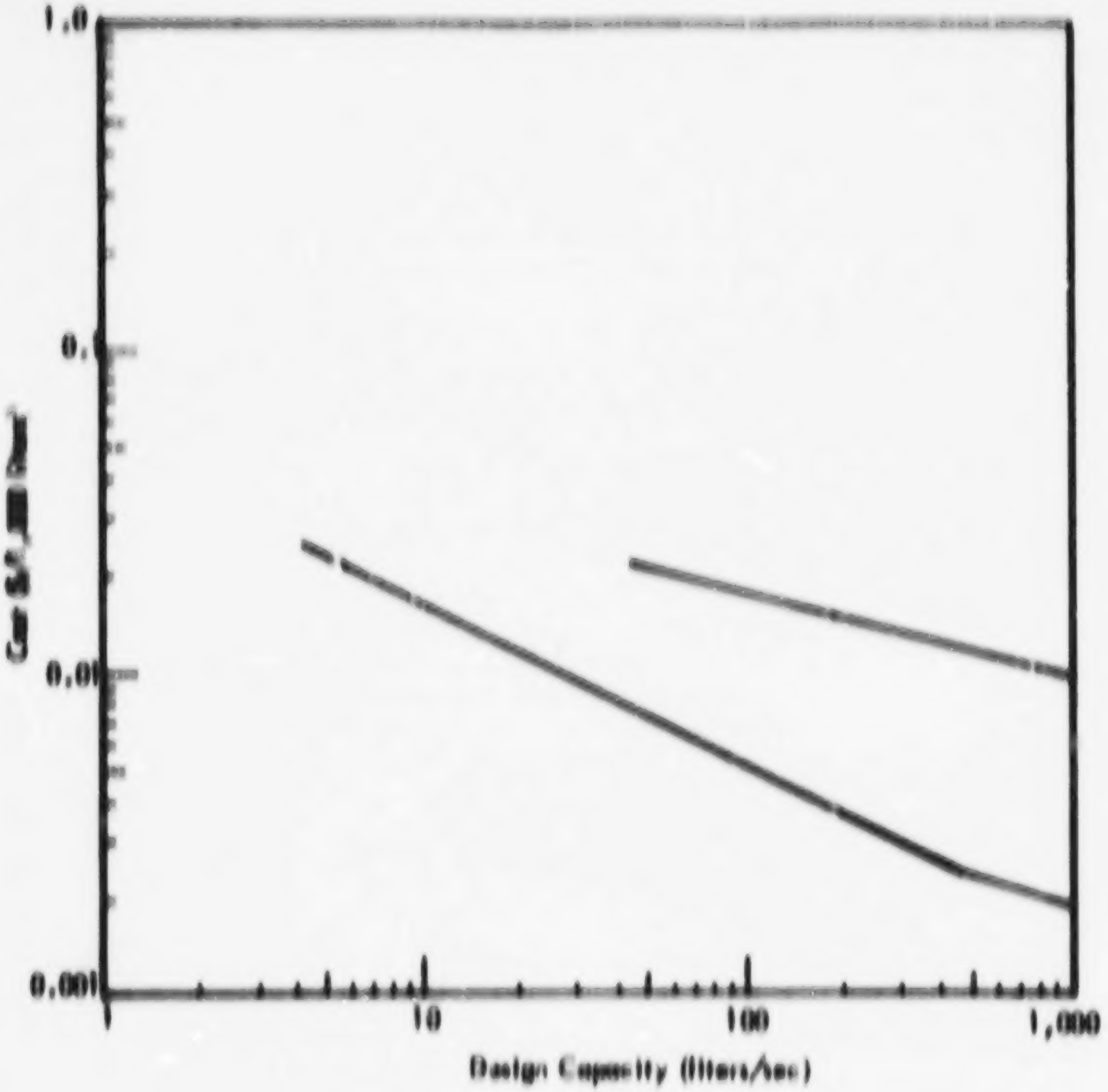
Time of Ozonation	Ozone Absorbed (mg/liter)	γ-BHC		Dieldrin		DDT		TDE (DDD)	
		Before Ozonation	After Ozonation	Before Ozonation	After Ozonation	Before Ozonation	After Ozonation	Before Ozonation	After Ozonation
		µg/liter							
5	8.8	1.22	0.88	1.29	1.08				
10	18.3	1.29	0.57	1.28	0.66				
20	36.0	1.31	0.34	1.37	0.22				
5	11.7					2.15	0.58	2.20	0.62
10	20.0					2.20	0.46	2.20	0.40
20	30.2					2.20	0.14	2.20	0.13

Source: [illegible]

to undergo decomposition in the presence of acid.[23] The four organophosphorus insecticides (Parathion, methyl Parathion, Demeton, Guthion) are readily hydrolyzed in an alkaline medium. The half-lives for Parathion and methyl Parathion in a 4N hydroxide solution are 22 minutes and 7.5 minutes, respectively.[19] According to Melnikov, the time required for 50 percent hydrolysis of the thiono-isomer of Demeton at 20C and pH 13 is 75 minutes, and that of the thio-isomer is 0.85 minutes.[21] Leigh observed that more than 98.5 percent of the Lindane was removed at pH 11.5 in 6.5 hours and a complete removal of DDT was obtained at pH 11.1 in less than 24 hours.[19]

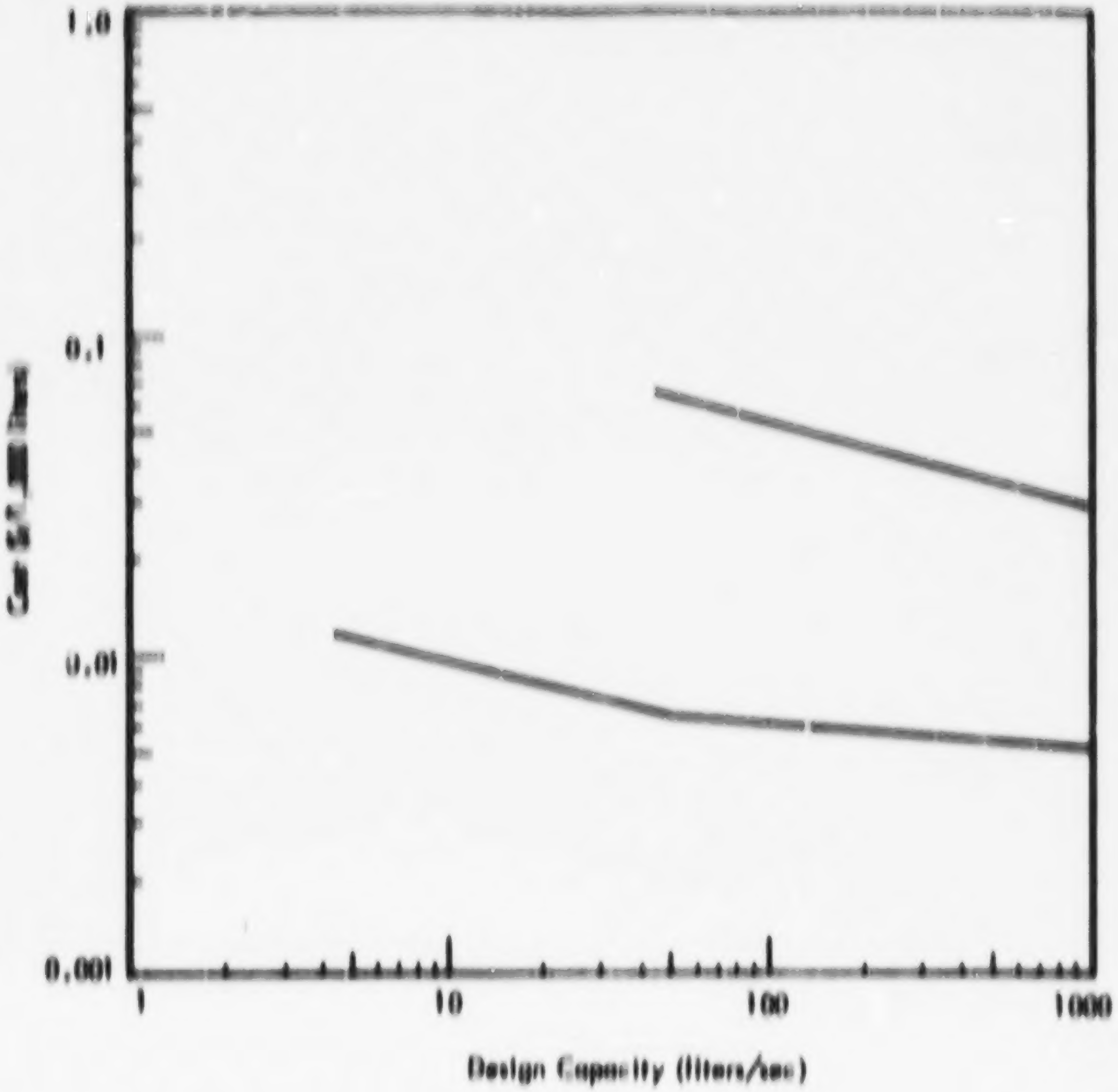
Ozonation Costs.

Capital costs were amortized at 7 percent over 20 years. Capital costs included building costs, contactor tank costs (concrete, baffles, lining), ozonators, driers, pumps, pipes, and controls. Maintenance costs were calculated at 2 percent of building and contactor tank costs and 8 percent of ozonator and drier costs. Power costs were estimated at $0.03/kwhr and 22 kwhr/kg of ozone. An ozone dosage of 10 mg/liter was used. Labor was not included in the cost calculations. The lower cost curves were based on manufacturers claims and the upper curves were derived from published reports. Figures IV-8, IV-9, and IV-10 present, respectively, capital costs, operation and maintenance cost, and total cost of ozonation. Land requirements for ozonation, derived from in-house information and manufacturers' claims, are presented in Figure IV-11.



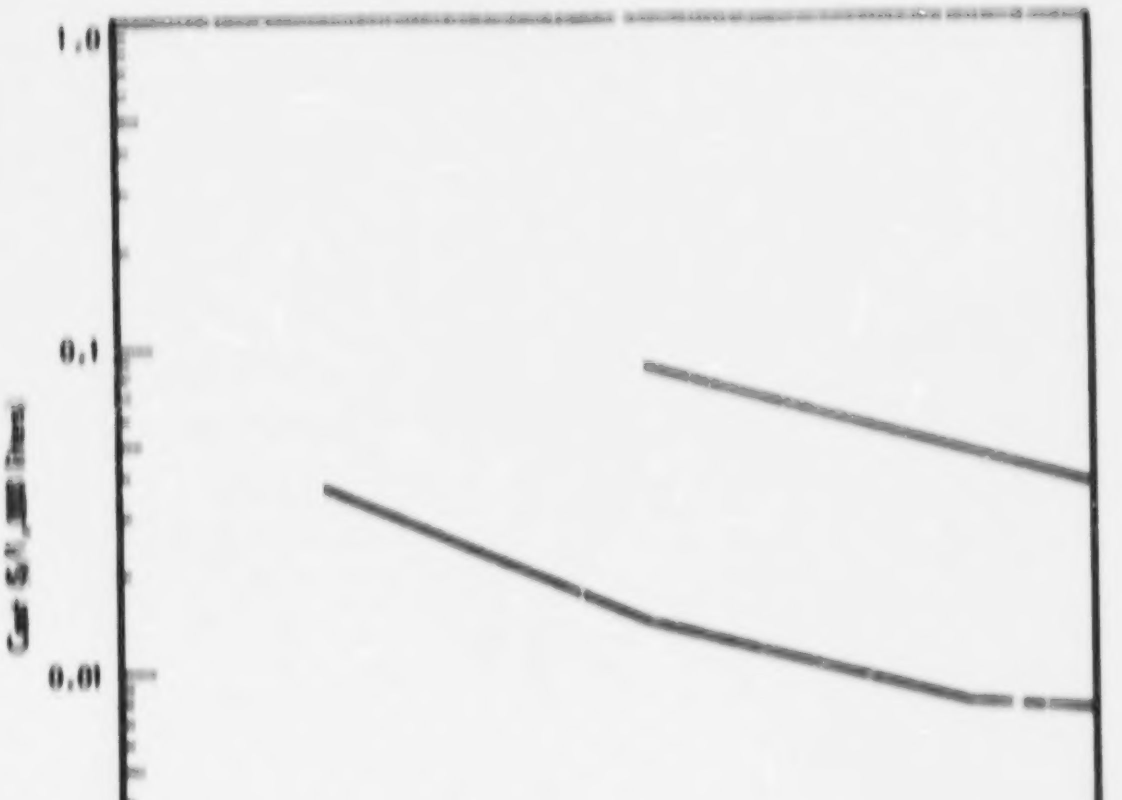
Source: See Figure A-4.

FIGURE IV-8
OZONATION: CAPITAL COST RANGE
1974



Source: See Figure A-5.

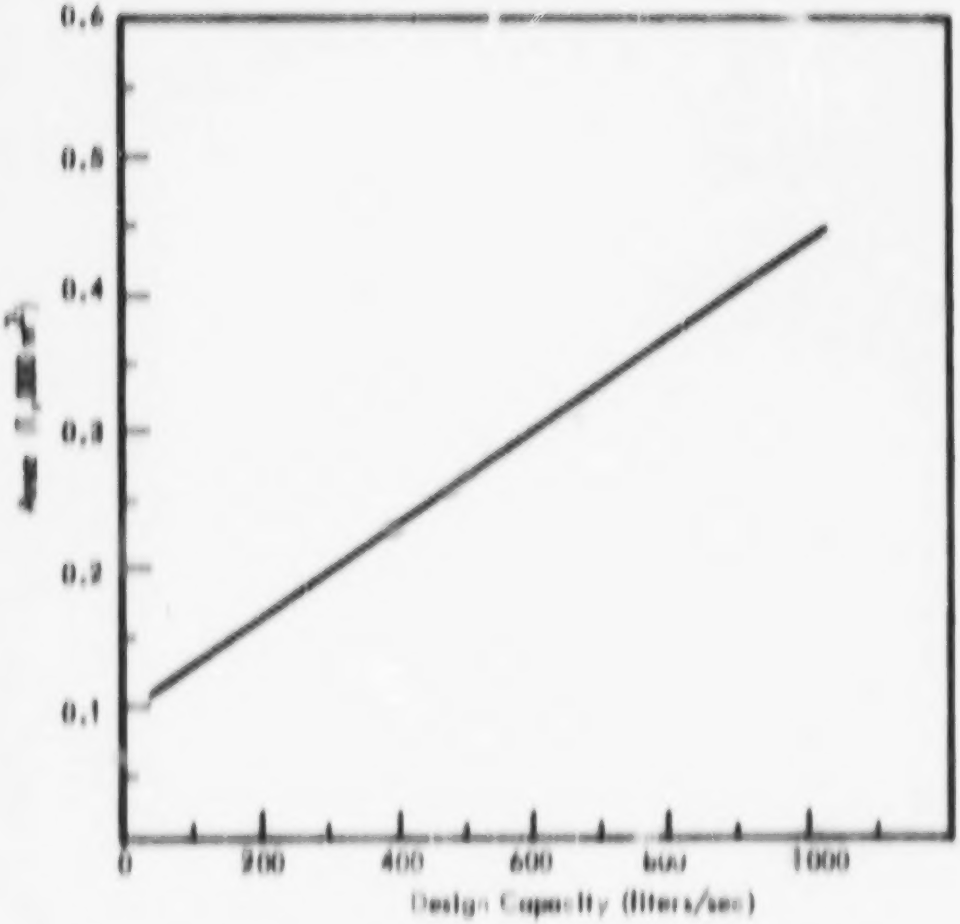
FIGURE IV-9
OZONATION: OPERATION
AND MAINTENANCE COST RANGE
1974



Source: See Figure A-4.

FIGURE IV-10

OZONATION: TOTAL COST RANGE
1974



Source: 198.

FIGURE IV-11
OZONATION: LAND REQUIREMENTS

Coagulation/Precipitation

Process Description.

Coagulation and precipitation are processes which change the physical or chemical properties of dissolved, colloidal, or suspended solids to such an extent that they will settle out of solution by gravity. A coagulant either changes surface charge properties to the extent that particles will tend to agglomerate or it enmeshes particles in a polymeric suspension. In either case, the final products are large, agglomerated particles (or flocs) which more readily settle under the influence of gravity. A precipitant is a chemical which will react with a soluble species to form an insoluble compound which precipitates out of solution. Often coagulated or precipitated particles are also removed by filtration after sedimentation. See Table IV-2 for a summary of solubilities of inorganic salts.

Particle coagulation results from the destabilization of stable suspended and dissolved solids and colloids. Stability is due to electrical charge and solvation effects. Destabilization is accomplished by the addition of cationic polyelectrolytes or cationic electrolytes such as Al^{+3}, Fe^{+2}, or Fe^{+3}; the formation of charged hydrous oxides such as $Al_x(OH)_y^{+n}$; the natural coagulation of anionic and cationic polyelectrolytes; or the entrainment in hydrous oxide flocs. Destabilization is most effective when the contaminant solids come in contact with small charged micronuclei of hydrous oxide. When followed by flocculation to generate larger particles, the solids can be removed by sedimentation, flotation, or filtration.

To accomplish coagulation or precipitation, chemical coagulants or precipitants are added to the raw water in solid, slurry, or solution form. The chemicals and influent are mixed for 1 to 2 minutes in a rapid mix tank (see Figure IV-12) followed by a slow mix of about 30 minutes to stimulate particle growth. Several hours in a clarifier (see Figures IV-13 and IV-14) are usually sufficient to separate the bulk of the solids from the water although filtration is often necessary (see Figures IV-15, IV-16, and IV-17). Dewatered solids can be recovered and recycled, incinerated, landfilled, used as fertilizer, or simply dumped in the ocean, depending on the nature of the waste, the chemicals added, and local regulations.

A number of chemical compounds are suitable for use as coagulants or precipitants. Common coagulants include alum ($Al_2(SO_4)_3 \cdot 14\,H_2O$), ferric chloride ($FeCl_3$), lime ($Ca(OH)_2$), ferrous sulfate ($FeSO_4$), clays, and natural and synthetic polymers. Precipitants include chlorine (Cl_2), potassium permanganate ($KMnO_4$), potassium ferrocyanide ($K_4Fe(CN)_6$), hydrogen sulfide (H_2S), sodium sulfide (Na_2S), soda ash (Na_2CO_3), caustic soda ($NaOH$), activated silica (SiO_2), and certain polymeric materials like chitosan. These categories are not rigid and some of these chemicals are classed as both coagulants and precipitants in the literature. This is due to a certain overlap and similarity in the physical processes involved

TABLE IV-2

SOLUBILITIES OF PARTICULAR INORGANIC SALTS
mg/liter

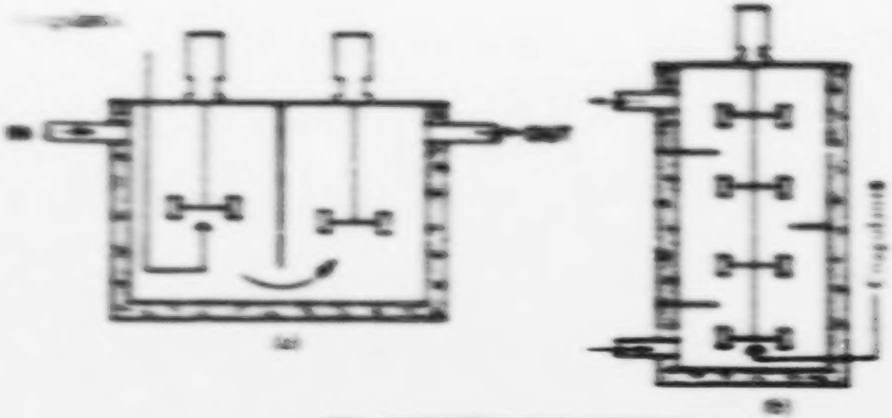
	Cations								Anions			
	Sb	Be	Co	Li	Mo	Ni	W	V	SbO_2^-	MoO_4^{-2}	WO_4	VO
Carbonate	o	I	I	10^4	o	I	-	-	-	-	-	-
Chloride	10^5	S	10^6	10^6	I	10^6	I	S	-	-	-	-
Ferrocyanide	o	o	I	S	o	I	-	-	-	-	-	-
Hydroxide	o	I	3.2	10^5	10^3	130	-	-	-	-	-	-
Sulfate	I	10^5	10^5	10^5	o	10^6	-	S	-	-	-	-
Sulfide	1.7	S	I	S	I	I	I	I	-	-	-	-
Calcium	-	-	-	-	-	-	-	-	-	I	6.0	-
Iron	-	-	-	-	-	-	-	-	-	I	-	I
Magnesium	-	-	-	-	-	-	-	-	I	10^5	I	-

S = Soluble, solubility ≥ 100 mg/liter but unknown

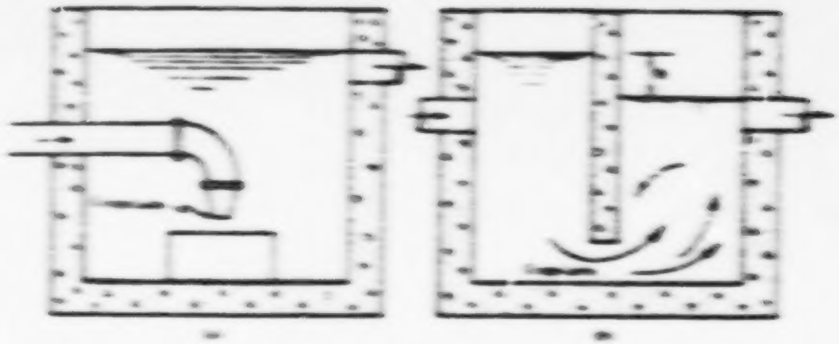
I = Insoluble, solubility < 10 mg/liter but unknown

No entry denotes no compound or no data

Numbers are solubilities in mg/liter at 20 C and 760 mm of Hg



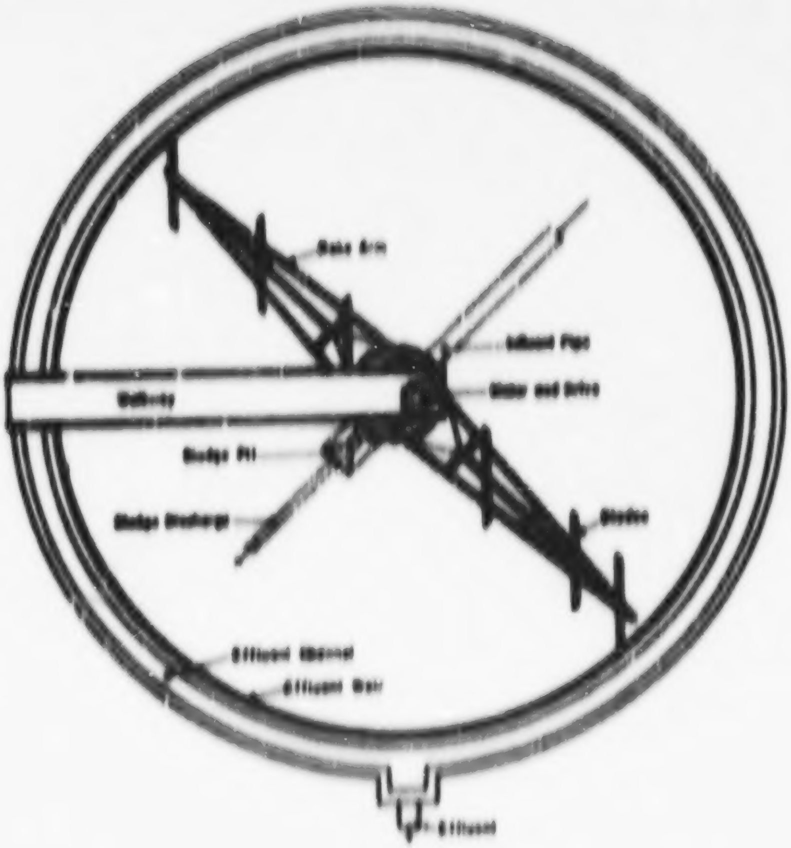
MECHANICAL



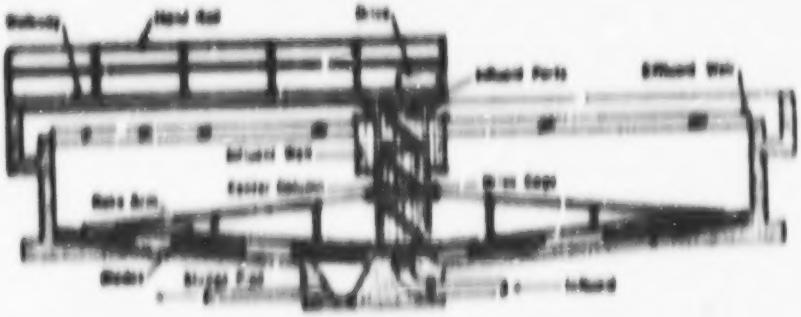
HYDRAULIC

Source: EPA

FIGURE IV-12
TYPES OF FLASH MIXERS


Rake Arm
Influent Pipe
Motor and Drive
Walkway
Sludge Pit
Sludge Discharge
Blades
Effluent Channel
Effluent Weir
Effluent

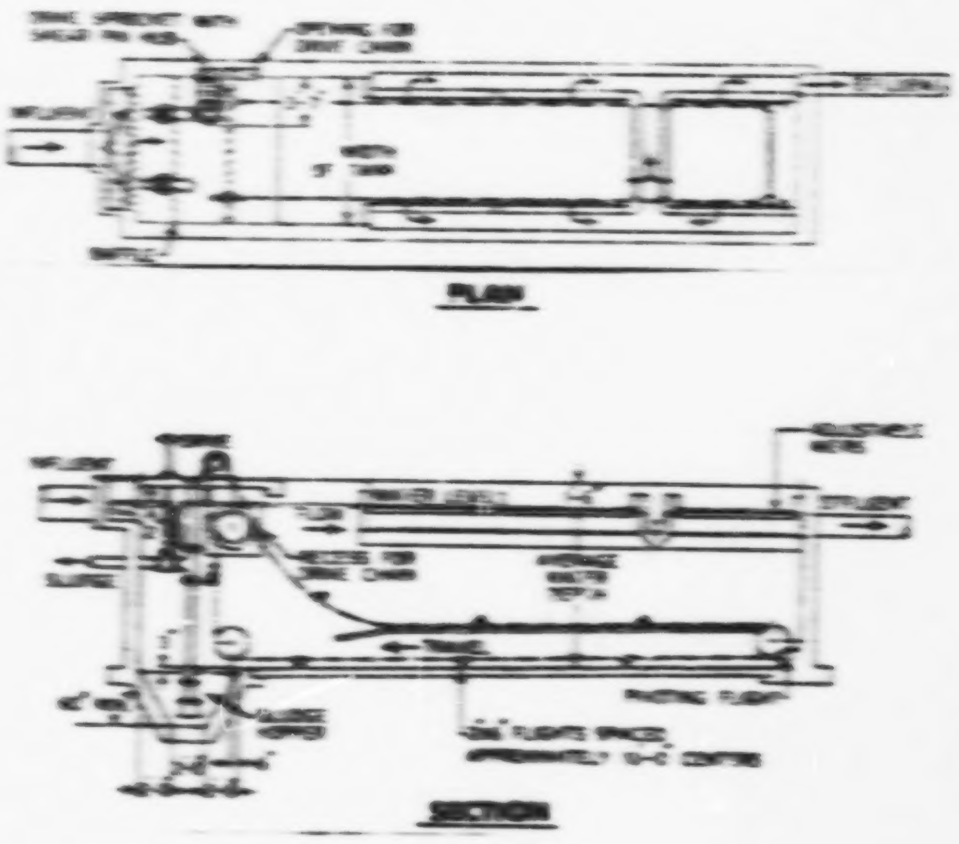
PLAN


Walkway
Hand Rail
Drive
Influent Ports
Effluent Weir
Effluent Well
Center Column
Drive Cage
Rake Arm
Blades
Sludge Pit
Influent

SECTION

Source: 195,

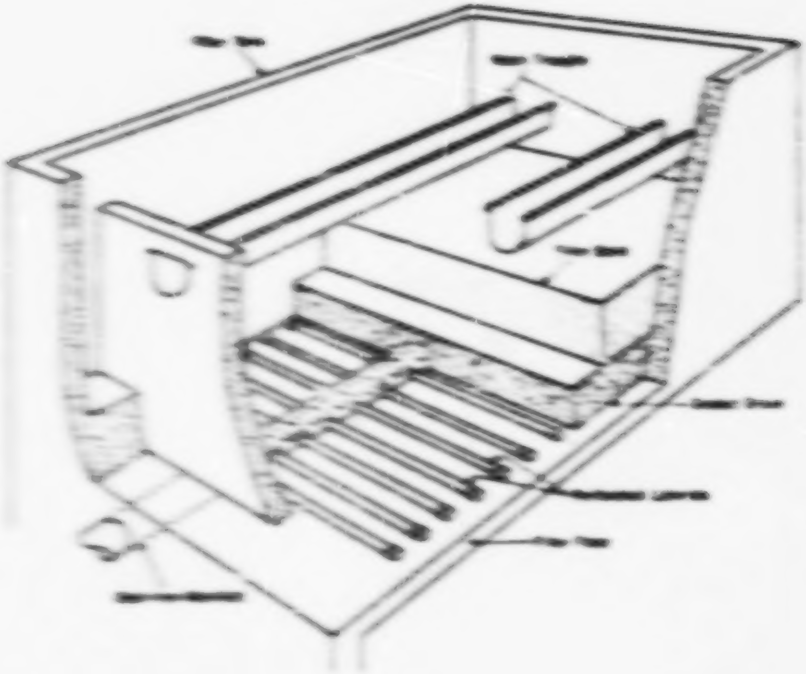
FIGURE IV-13
TYPICAL CIRCULAR CENTER-
FEED SEDIMENTATION TANK



INFLUENT
EFFLUENT
WIDTH OF TANK
PLAN
INFLUENT
EFFLUENT
SLUDGE
AVERAGE WATER DEPTH
SLUDGE HOPPER
SECTION

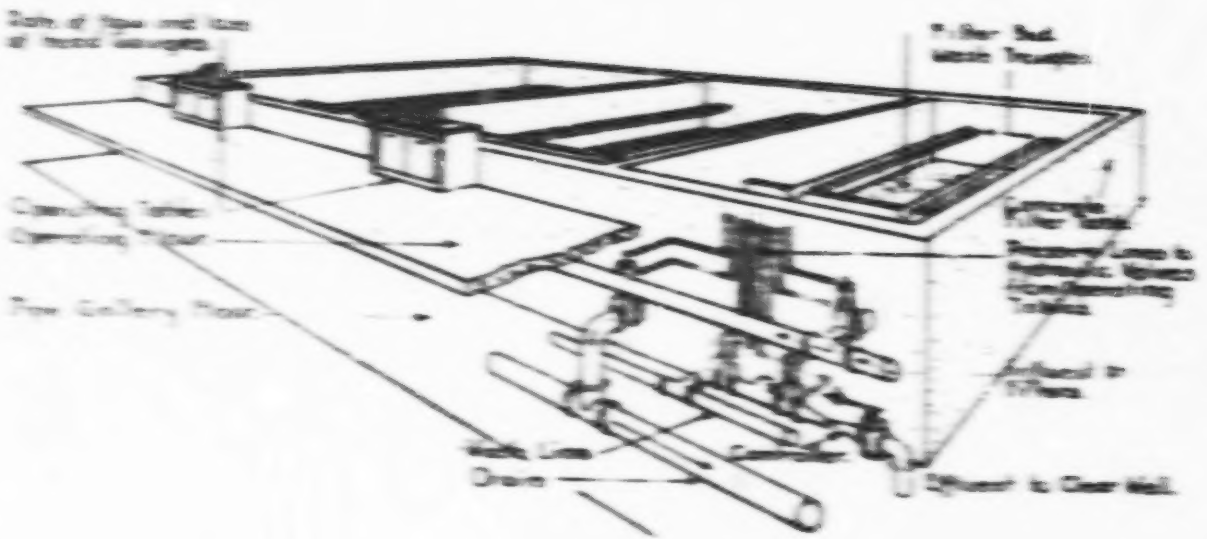
Source: [illegible]

FIGURE IV-4
TYPICAL RECTANGULAR
SEDIMENTATION TANK



Source: [illegible]

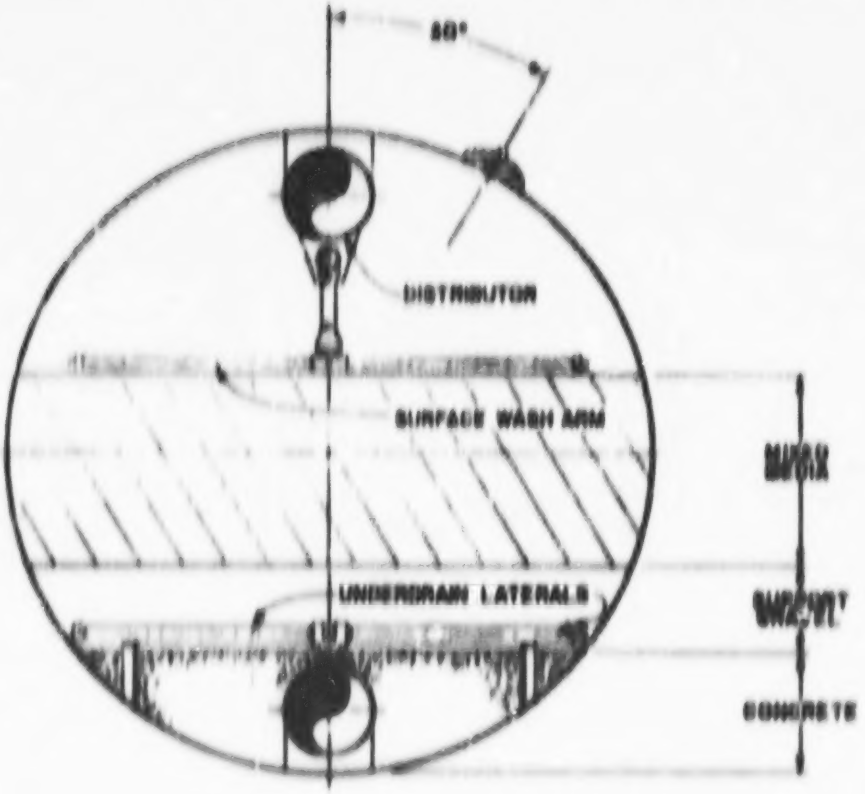
FIGURE IV-5
CUTAWAY VIEW OF TYPICAL
RAPID SAND FILTER



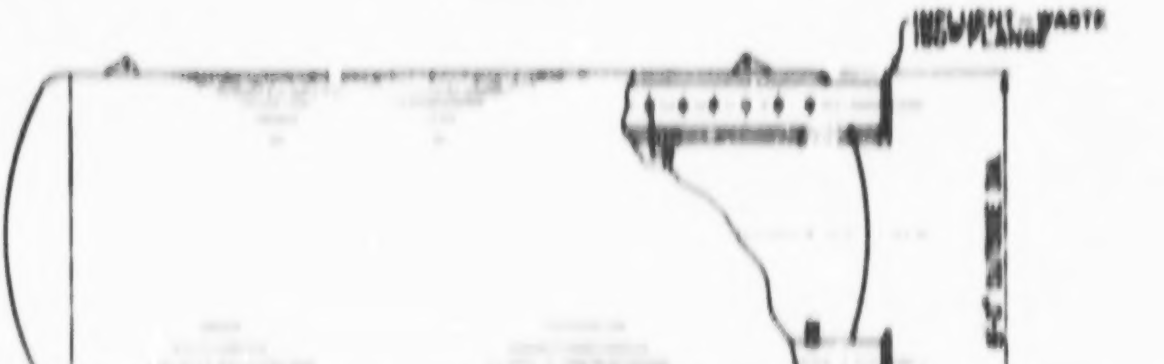
Rate of Flow and Loss of Head Gauges
Filter Bed
Wash Troughs
Concrete Filter Tank
Operating Table
Operating Floor
Pressure Lines to Hydraulic Valves from Operating Tables
Pipe Gallery Floor
Influent to Filters
Wash Line
Drain
Controller
Effluent to Clear Well

Source: 195.

FIGURE IV-16
GENERAL ARRANGEMENT OF A
RAPID SAND FILTER PLANT


60°
DISTRIBUTOR
SURFACE WASH ARM
MEDIA
UNDERDRAIN LATERALS
GRAVEL
CONCRETE

SECTION


INFLUENT – WASTE
150# FLANGE
EFFLUENT – BACKWASH
150# FLANGE

ELEVATION

Source: 198.

FIGURE IV-17
TYPICAL PRESSURE FILTER

Exact water treatment parameters will vary depending on the chemicals used and the nature of the water treated. Water with a total dissolved or suspended solids concentration of less than 50 mg/liter is more difficult to treat effectively than more concentrated waters because of the difficulty in forming flocs in such a dispersed system. Similarly, settling is greatly hindered when treating a water with greater than a 2000 mg/liter concentration of solids.

The control of pH can be very important, especially when dealing with ions whose chemical nature is pH dependent, such as carbonates or hydroxides. Alum coagulation treatment is favored at pH's of 5-7; alkaline pH's favor lime treatment. Usually chemical treatment must be followed by some sort of neutralization to stabilize chemically the water and return it to a pH near 7.

There are several technical problems associated with coagulation and precipitation. Both methods produce considerable quantities of sludge solids. For instance, alum produces 0.45 kg per 100 to 200 g of aluminum added. Lime produces 450 to 600 kg of sludge per 1000 m^3 of soft water.[58] Anhydrous ferric chloride produces about 50 kg of sludge per 1000 m^3 of soft water.[57] These large sludge quantities present considerable disposal problems. In designing a treatment process involving chemicals, the resulting sludge disposal problem must be taken into account.

With large quantities of solids present, scaling can also be a problem. If allowed to continue, scaling requires periodic plant shutdown for cleanup to prevent complete clogging. One way to avoid scaling is to use construction materials which are not readily susceptible to scaling, such as stainless steel or epoxy-reinforced fiberglass.

Application.

All the coagulation and precipitation processes and required chemicals so far discussed have been used in full-scale treatment plant applications. The same is not true for some of the specific applications to be discussed below. Many of these have been examined on a laboratory scale only. The basic processes, however, are well known and conventional.

Numerous tests have been conducted on several of the subject contaminants using lime as the coagulant. For instance, tests on water samples contaminated with antimony have yielded removal efficiencies better than 90 percent at a pH of 11.[57] Tests carried out on molybdenum solutions at a pH of 8.2, however, have yielded removal efficiencies of less than 10 percent.[57] A solution of 12 mg cobalt/liter was reduced to 1.4 mg/liter using lime at a pH of 9.5.[57] Several researchers have reported different results for nickel. Nilsson[4] reported a reduction from 16 to 6 mg/liter at a pH of 9.5. Dean[44] reported reductions from 2935 to less than 1 mg/liter at a pH of 11.1 after 30 minutes of contact time and settling. Other researchers[57] have reported reductions in nickel from 160 to 0.08 mg/liter at a pH of 8.7. Patterson[65] reported that 100 mg/liter nickel was reduced to 1.5 mg/liter at a pH of 9.9 with the addition of 250 mg/liter lime; 5 mg/liter was reduced to 0.35 mg/liter at a pH of 10 with 260 mg/liter lime and 30 mg/liter ferrous sulfate followed by sedimentation and mixed media filtration; and 5 mg/liter was reduced to 0.15 mg/liter at a pH of 11.5 with 600 mg/liter lime followed by sedimentation and filtration. Some testing has also been done on various chlorinated hydrocarbon and organo-phosphorus insecticides using lime. At initial insecticide concentrations of 10 mg/liter, removal efficiencies of 98 percent for DDT, 55 percent for Dieldrin, 35 percent for Endrin, less than 10 percent for Lindane, and 80 percent for Parathion were recorded.[18]

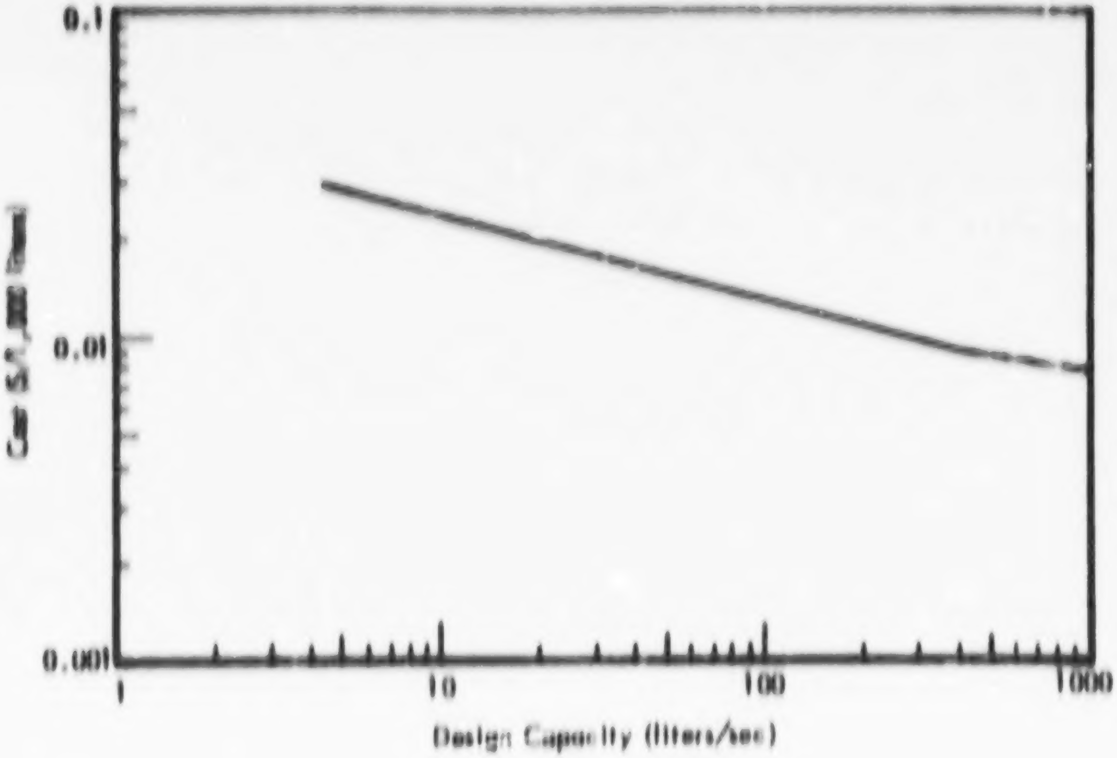
Alum is another commonly used coagulant. Tests on nickel solutions have yielded reductions from 16 to 11.7 mg/liter.[37] Research with solutions of vanadium using either ferric chloride or alum yielded reductions from 249 to about 1 mg/liter.[156] Alum was used at a pH of 8.5 and in ratios (by weight) of aluminum to vanadium of 80 to 100. Tests with ferric chloride were carried out at iron to vanadium ratios of 3 to 10 and at a pH of 8.5–9. NH_4OH was used to adjust the pH and two hours of contact and settling time were allowed. Using alum followed by sand filtration, DDT concentrations were reduced from 10 mg/liter to about nil, but Lindane was reduced by less than 20 percent.[19] Two sets of experiments using alum alone yielded reduction in DDT concentrations from 10 to 0.2 μg/liter and from 25 to 0.75 μg/liter.[39] Effects of alum on Parathion were negligible.[39]

A new polymer called chitosan is showing promise of being an effective water and wastewater treatment chemical. It is a natural polymer derived from crab shells, but can be synthesized on a commercial scale relatively cheaply and easily.[154] Experiments conducted with a variety of metals have shown excellent results. Chitosan is insoluble in water and is added to the water to be treated in an acetic acid solution. As soon as it is added to the water, the chitosan precipitates in large flocs which chelate and adsorb transition metals. Lab-scale tests have been conducted on cobalt, nickel, molybdenum, and tungsten. Cobalt and nickel solutions of 50 mg/liter each were treated with 100 mg of chitosan for 30 minutes for removal efficiencies of 62 and 90 percent, respectively.[153] Using 200 mg of chitosan, tungsten concentrations were reduced from 500 to 170 mg/liter and molybdenum concentrations were reduced from 2500 to 36 mg/liter.[153] Reportedly, removal efficiencies for vanadium are also very high,[154] but no data were available. Chitosan sludges are easily destroyed by incineration.

There are several more specialized, less common precipitants in use, such as potassium ferrocyanide, soda ash, sodium or hydrogen sulfide, and caustic soda.[29] Hydrogen sulfide dissolved in hydrochloric acid and added to a water sample will precipitate antimony to the solubility of antimony sulfide.[62,63] Sulfides will precipitate most metals present in a cationic form. Waters treated with sulfides require some sort of post-treatment, such as the addition of ferrous sulfate, to remove excess sulfides.

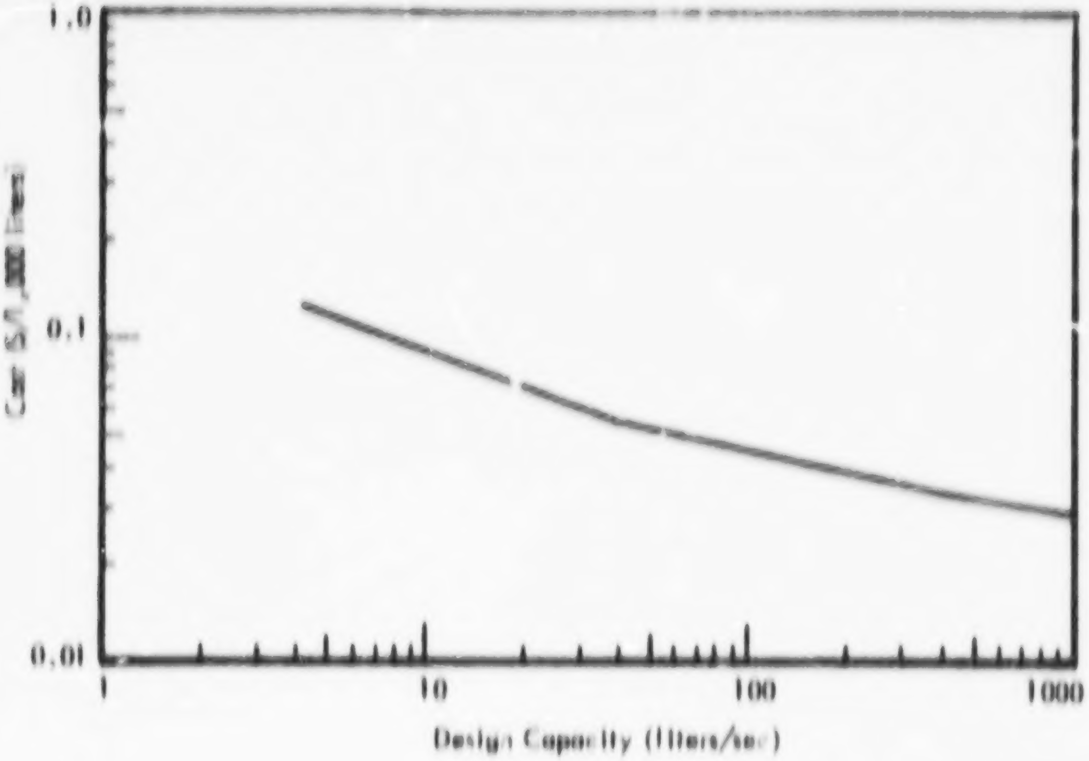
Coagulation/Precipitation Costs.

Capital costs were amortized at 7 percent over twenty years. Maintenance was estimated at 3 percent of capital. Salaries were assumed constant. Chemical costs used were \$0.13/kg for lime, \$1.76/kg for H_2S, and \$16.50/kg for chitosan. H_2S costs include gas delivery equipment. Chitosan costs include acetic acid. The total chemical costs depend on the concentrations of susceptible material in the water. For H_2S and chitosan which precipitate all of the heavy metals, a range of 0.1 to 10 mg/liter was used. For lime, a concentration range of 0.1 to 750 mg/liter was used. Operation and maintenance costs do not include sludge disposal, but do include sedimentation and filtration. Figures IV-18, IV-19, and IV-20 present capital, operation and maintenance, and total costs for lime coagulation. Figure IV-21 presents land requirements for lime coagulation. Land requirements were calculated from in-house information and manufacturers' literature. Figures IV-22 through IV-25 present operation and maintenance and total costs for chitosan coagulation for cobalt, nickel, tungsten, molybdenum, and vanadium and for antimony removed by hydrogen sulfide precipitation.



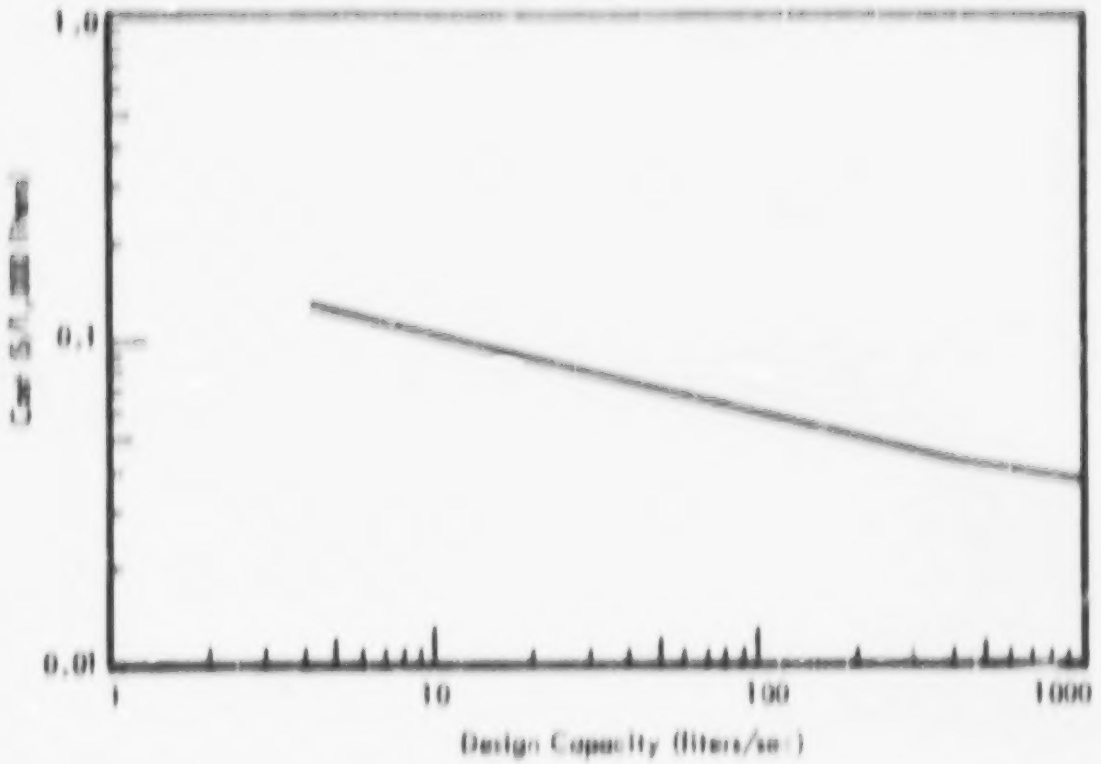
Source: See Figure A-7.

FIGURE IV-18
LIME COAGULATION, SEDIMENTATION,
AND FILTRATION: CAPITAL COST
1974



Source: See Figure A-8.

FIGURE IV-19
LIME COAGULATION, SEDIMENTATION,
AND FILTRATION: OPERATION AND
MAINTENANCE COSTS
1974



Source: See Figure A-9.

FIGURE IV-20
LIME COAGULATION, SEDIMENTATION,
AND FILTRATION: TOTAL COST
1974

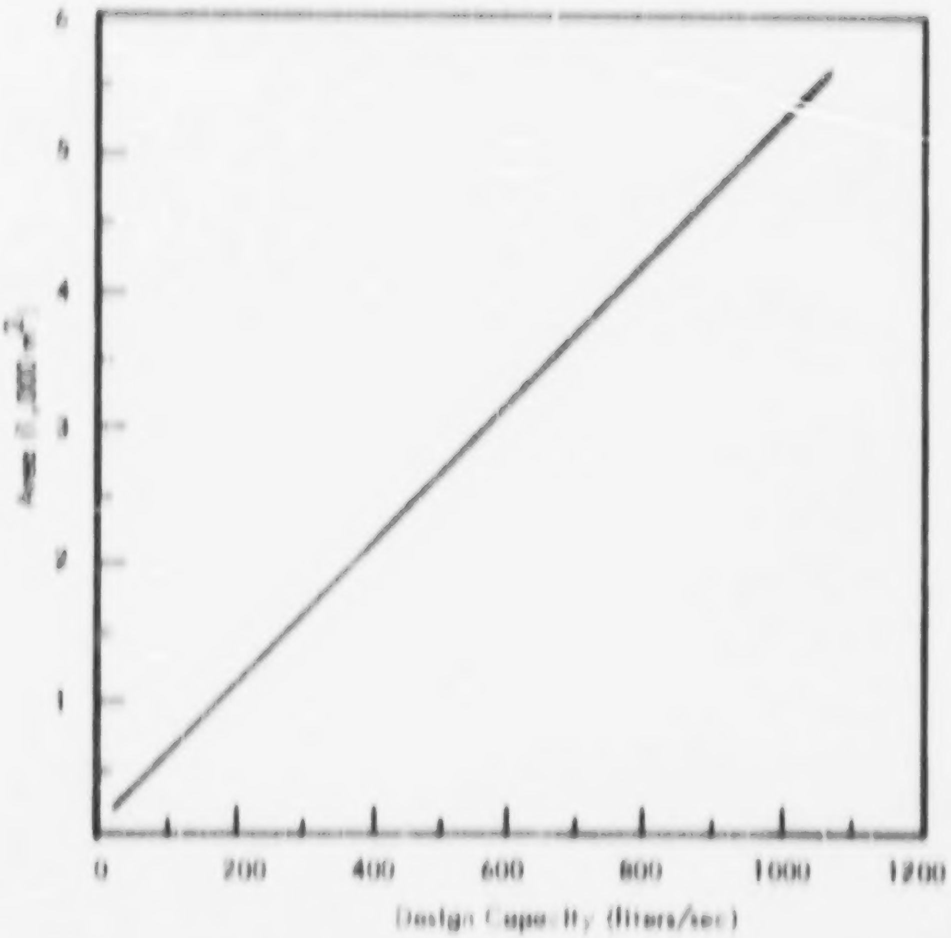


FIGURE IV-21
LIME COAGULATION, SEDIMENTATION,
AND FILTRATION: LAND REQUIREMENTS

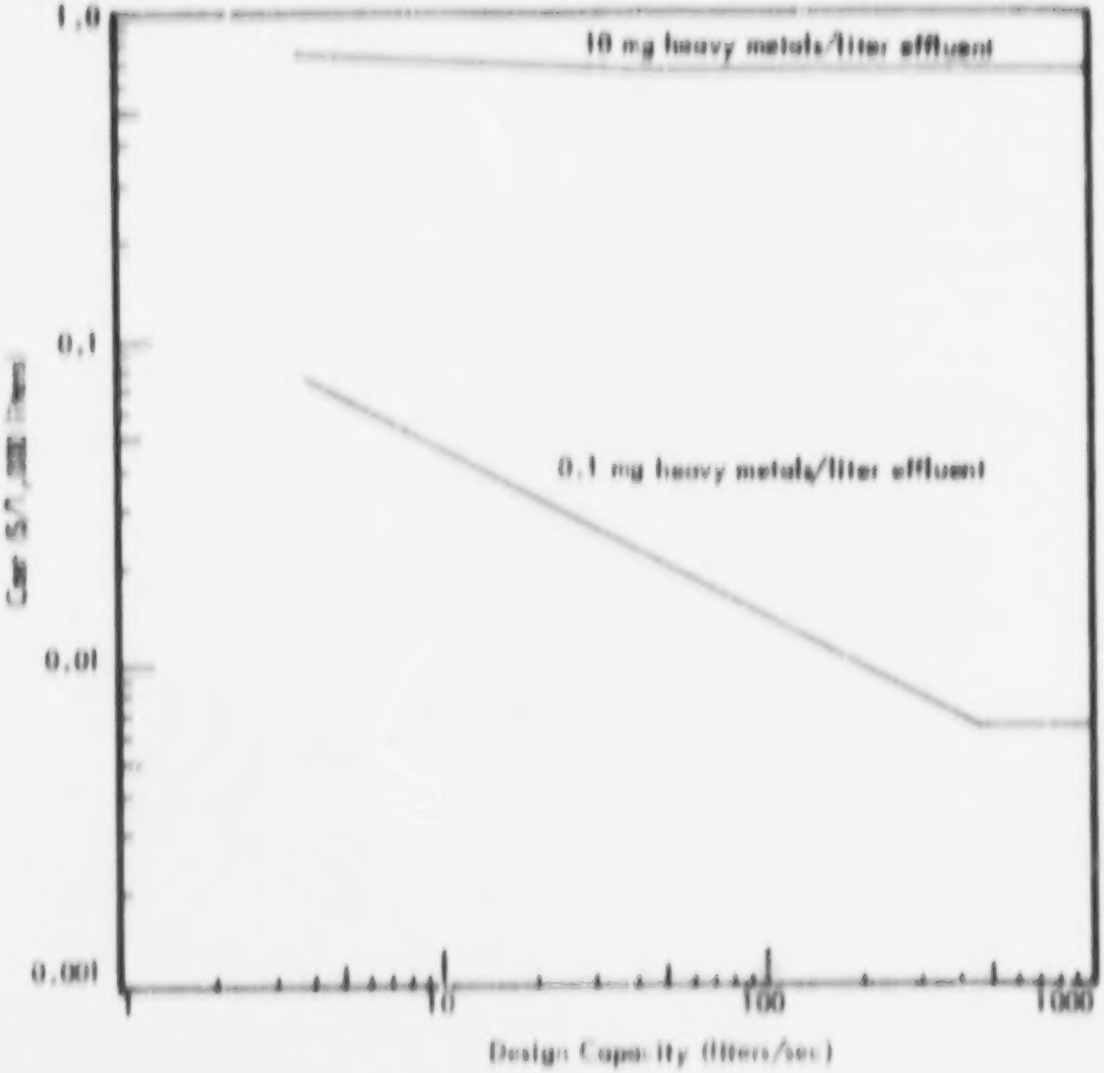
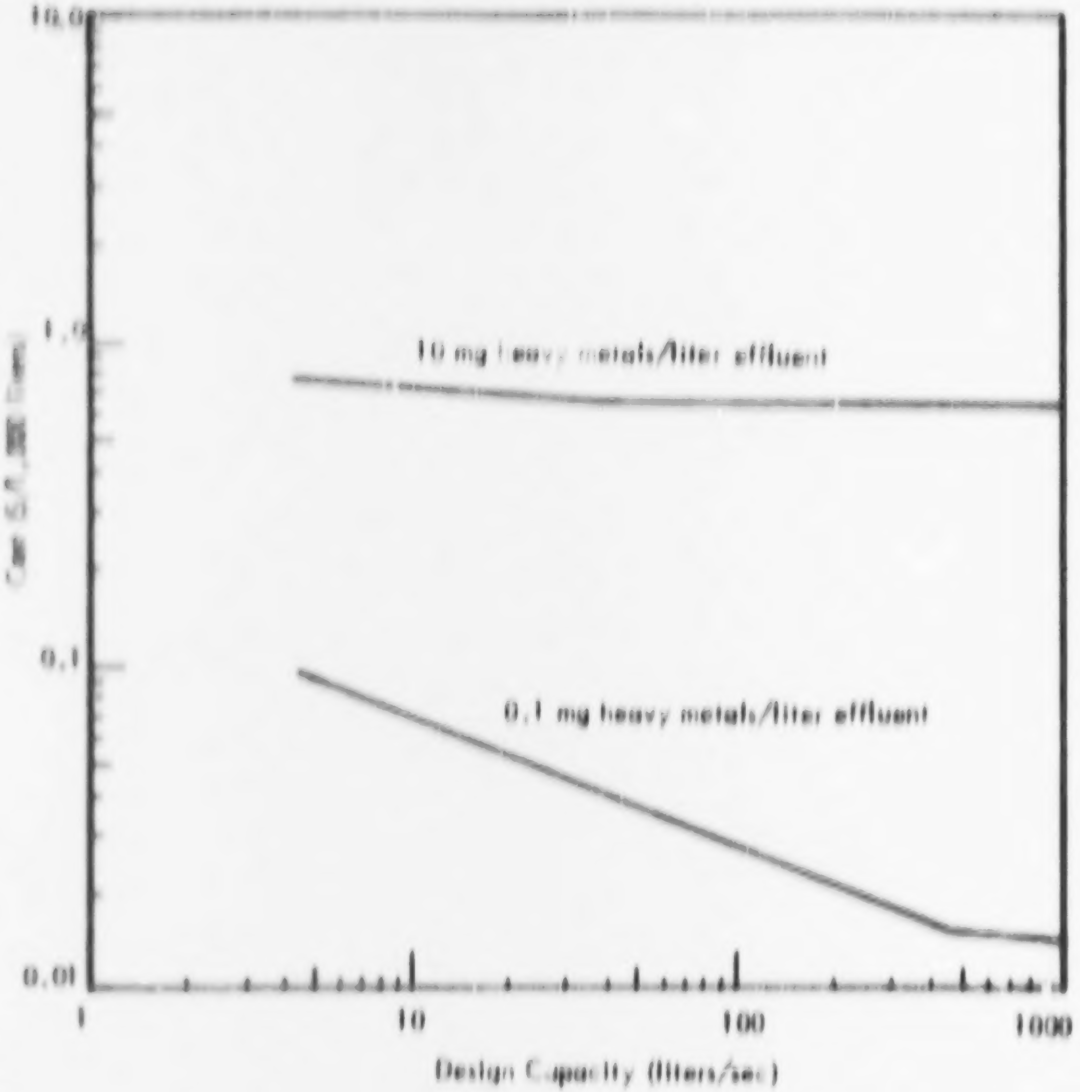


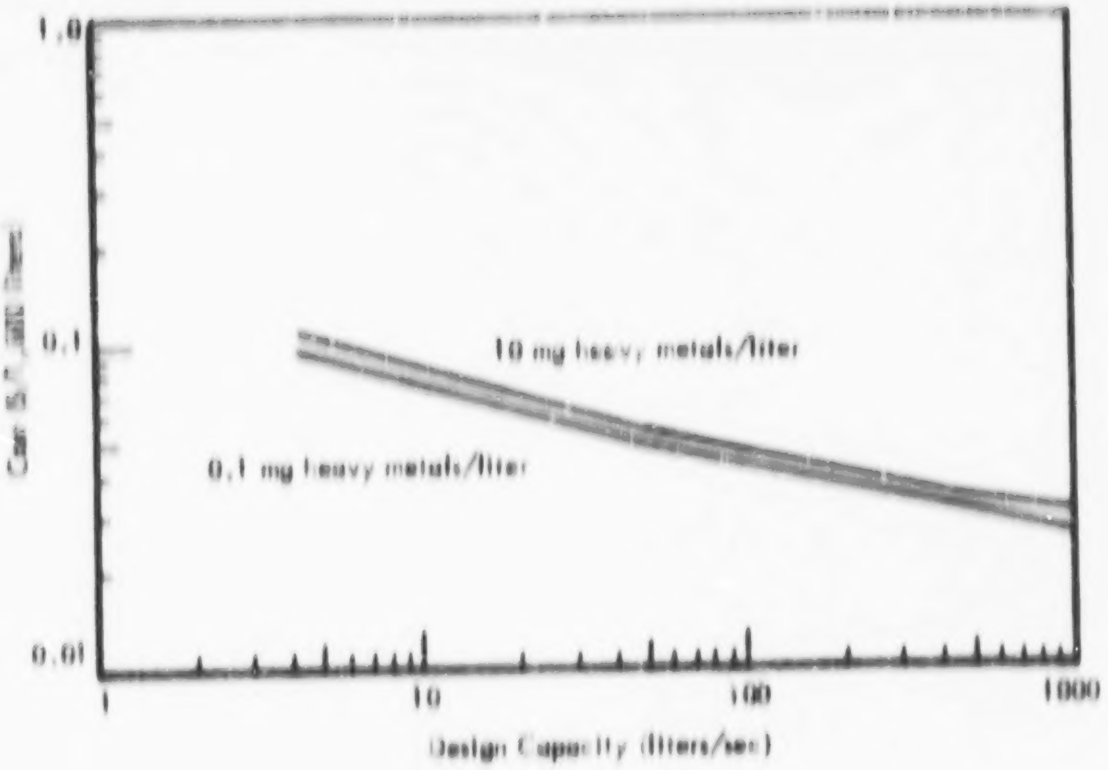
FIGURE IV-27
CHITOSAN COAGULATION FOR COBALT,
NICKEL, TUNGSTEN, MOLYBDENUM,
AND VANADIUM: OPERATION AND
MAINTENANCE COST RANGE
1971

Source: See Figure A-10.



Source: See Figure A-11.

FIGURE [illegible]
CHITOSAN COAGULATION FOR COBALT,
NICKEL, TUNGSTEN, MOLYBDENUM
AND VANADIUM; TOTAL COST RANGE
1974



Source: See Figure A-12.

FIGURE IV-24

ANTIMONY REMOVAL WITH HYDROGEN SULFIDE:
OPERATION AND MAINTENANCE COST RANGE
1974

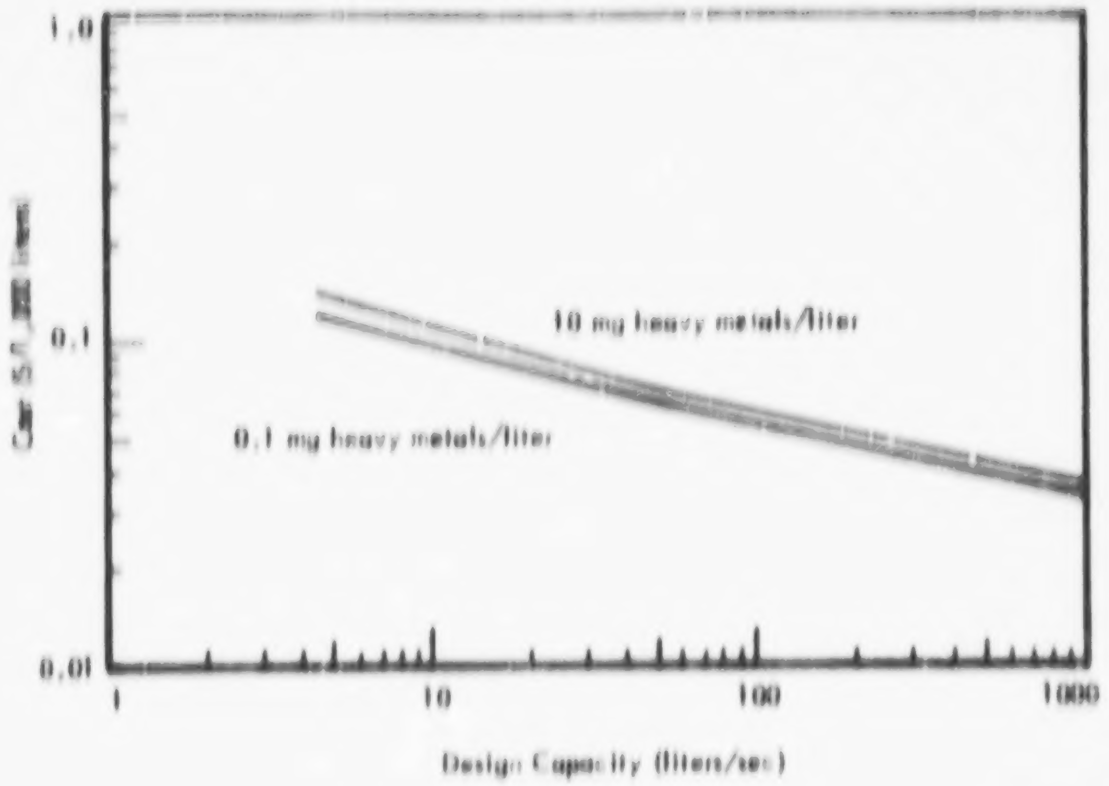


FIGURE IV-29

ANTIMONY REMOVAL WITH HYDROGEN SULFIDE:
TOTAL COST RANGE

1974

Source: See Figure A-13.

Distillation

Process Description and Theory.

Distillation involves the separation of water from the non-volatile components of a solution by conversion of the water from a liquid to a vapor followed by condensation of the vapor apart from the influent. Ideally, the process should provide a product water 100 percent free of non-volatile contaminants. Realistically, product waters can range from 500 to less than 1 mg/liter dissolved solids, depending on the type of distillation system.

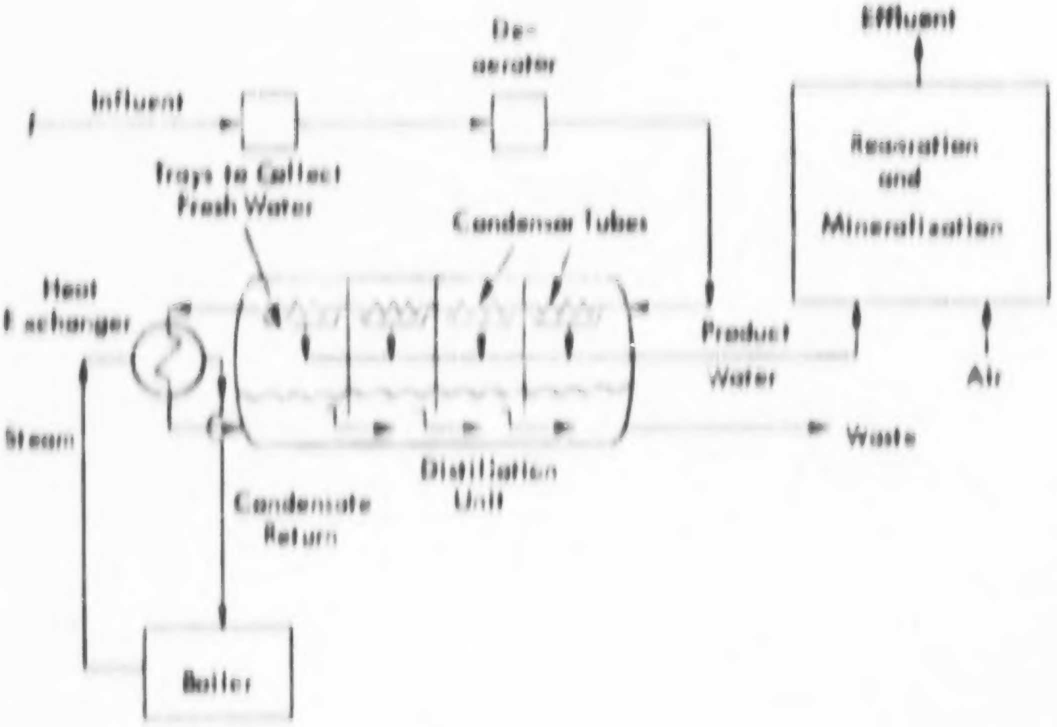
Distillation is an expensive method of water purification. Although scale economies do exist, the process is economically unfeasible except when (1) only highly brackish or salt water is available for potable use, (2) inexpensive waste heat is available, (3) a very high degree of treatment is required, or (4) contaminants cannot be removed by any other method. Several full-scale plants are presently in operation.

The major problems associated with distillation relate to power requirements, corrosion, scaling, and cost. For example, an influent stream of 3.5 percent (36 g/liter) NaCl at 25C theoretically requires at least 90 kwh/1,000 liters of pure water. Furthermore, because of many thermodynamic irreversibilities in the distillation process, actual processes operate at less than 10 percent of the optimum thermodynamic efficiency.

As water evaporates in the distillation process, dissolved salts become increasingly concentrated in the remaining brine. Eventually, the concentration exceeds the solubility of the dissolved salts and calcium carbonate, calcium sulfate, and magnesium hydroxide scales form. These can plug piping and reduce heating efficiency and must be removed; pH control can minimize the problem. Concentrated solutions of inorganic salts can also be very corrosive. Consequently, only certain corrosion-resistant metals can be used in their construction such as cupronickel alloys, aluminum, and titanium.

Minor problems include carryover of volatile contaminants, especially ammonia and organic compounds. Ammonia carryover can be avoided by lowering the pH of the feed to less than 3, but this can increase corrosion. Volatile organic compounds can foul heat transfer surfaces and cause taste and odor problems in the effluent. Lowering the distillation temperature helps. Both carryover problems can be fairly well dealt with by various conventional pre- and post-treatment methods.

Three distillation methods are commercially important: boiling type with long tube vertical evaporator, flash evaporation, and forced circulation with vapor compression. In multistage flash evaporation (Figure IV-26), influent water is pumped through heat transfer units in each of the several stages. Steam from the influent water condenses on the outside of the tubes and is collected in trays. The concentrated wastewater cascades from one stage to the next as a result of the pressure differential until it reaches the lowest


Effluent
De-aerator
Influent
Reaeration and Mineralization
Trays to Collect Fresh Water
Condenser Tubes
Heat Exchanger
Product Water
Air
Steam
Waste
Distillation Unit
Condensate Return
Boiler

Source: 55.

FIGURE IV-26
MULTISTAGE FLASH
EVAPORATION DISTILLATION

stage, where it is pumped out. Although this process is less efficient thermodynamically than ordinary evaporation, construction costs are lower. The influent water must be treated for removal of suspended solids and deaerated before it can be pumped through the system.

In vapor compression evaporators, influent water is heated to less than boiling and the evaporated vapor is compressed and returned to serve as the heating medium. This process requires partial vacuum conditions. The commercial applicability of the configuration is limited by the capital cost of the vapor compressors.

The third type, vertical tube evaporation, holds the most promise for future large-scale desalination plants. Tests have indicated 15 to 20 percent higher performance ratios than other designs with fewer problems of scale formation. In a three-stage unit (Figure IV-27), pretreated influent water enters the heat exchanger in the last stage and continues to warm up as it passes through the other heat exchangers. Influent water moving through the heat exchangers condenses the steam from the various heating units. When the hot influent water reaches the first stage, it flows down through vertical steam-heated tubes. The wastewater from the bottom of the first heating unit becomes the feed to the second.

Application.

Although no data were located concerning the use of distillation for removing any of the twelve subject contaminants, the very nature of the process makes it obvious that nonvolatile contaminants can be removed up to 100 percent,especially when dealing with influents of low concentrations such as would be expected with these contaminants. The process would probably be most applicable to treating water containing cobalt, lithium, molybdenum, nickel, tungsten, and vanadium. Antimony and beryllium are volatile enough that there might be a carryover problem. All of the organic compounds would present carryover problems.

Distillation Costs.

Capital cost was estimated using a 7 percent amortization rate over 20 years. Operation and maintenance included labor, tube replacement, fuel, chemicals(H_2SO_4), and power ($0.02/kwhr). Figures IV-28, IV-29, and IV-30 present, for the multistage flash process, estimates of capital, operation and maintenance, and total costs. The curves represent the range of values in the literature. Figures IV-31, IV-32, and IV-33 present the same information for distillation by the combined vapor compression, vertical tube evaporator, multistage flash process. Figure IV-34 presents an estimate of land requirements for either process.

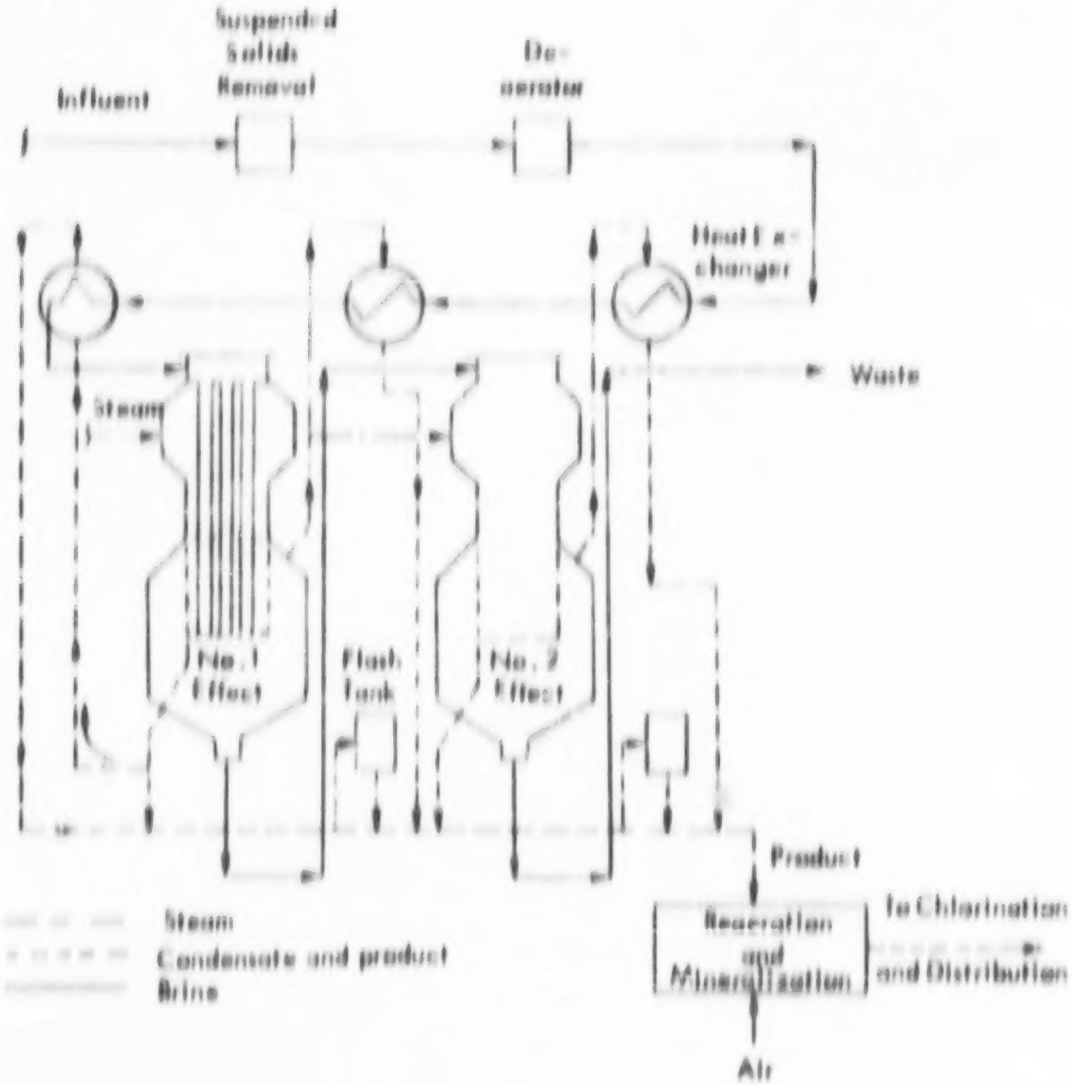
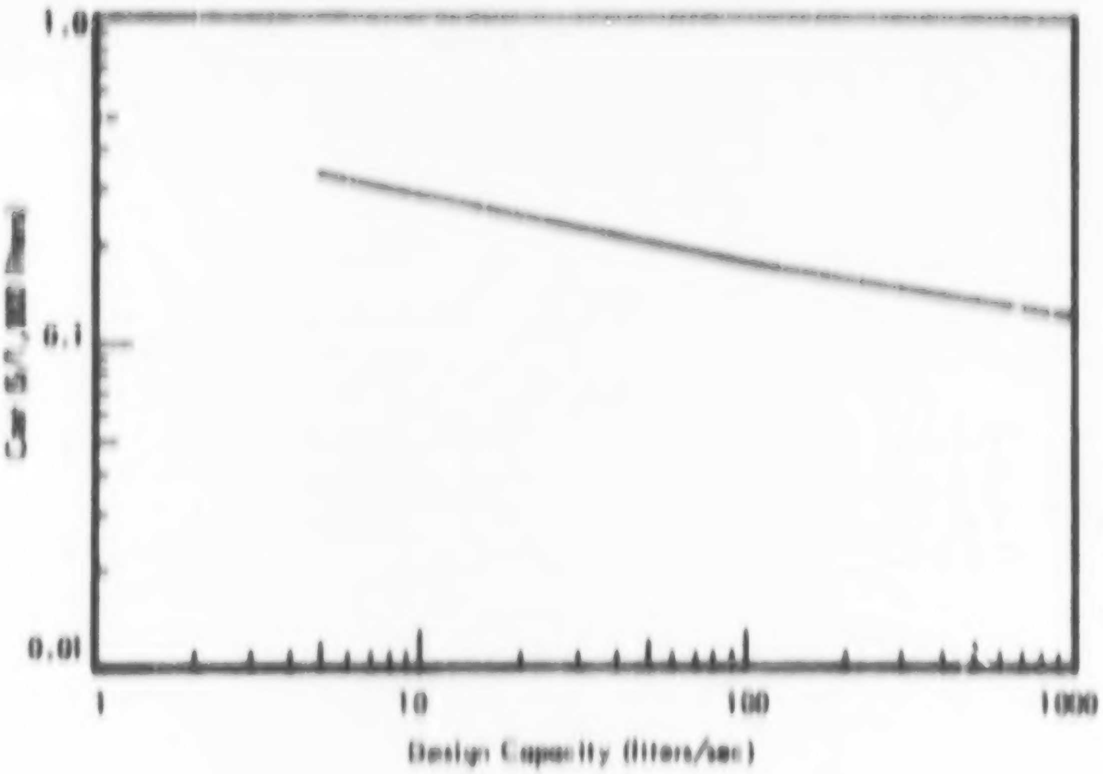

Suspended Solids Removal
Influent
De-aerator
Heat Exchanger
Waste
Steam
No. 1 Effect
Flash Tank
No. 2 Effect
Product
Reaeration and Mineralization
To Chlorination and Distribution
Air
Steam
Condensate and product
Brine

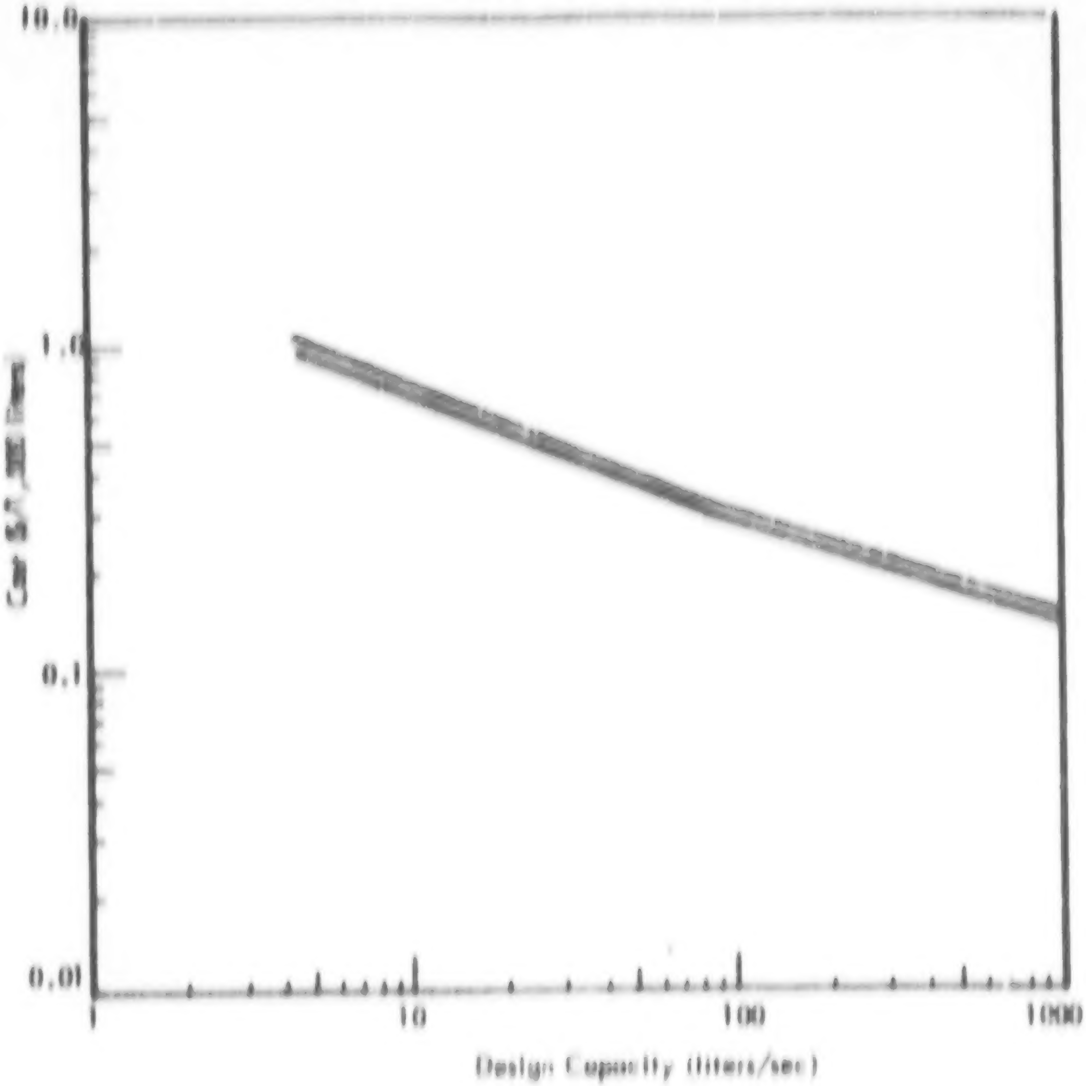
FIGURE IV-27
VERTICAL TUBE
EVAPORATOR

Source: 55.



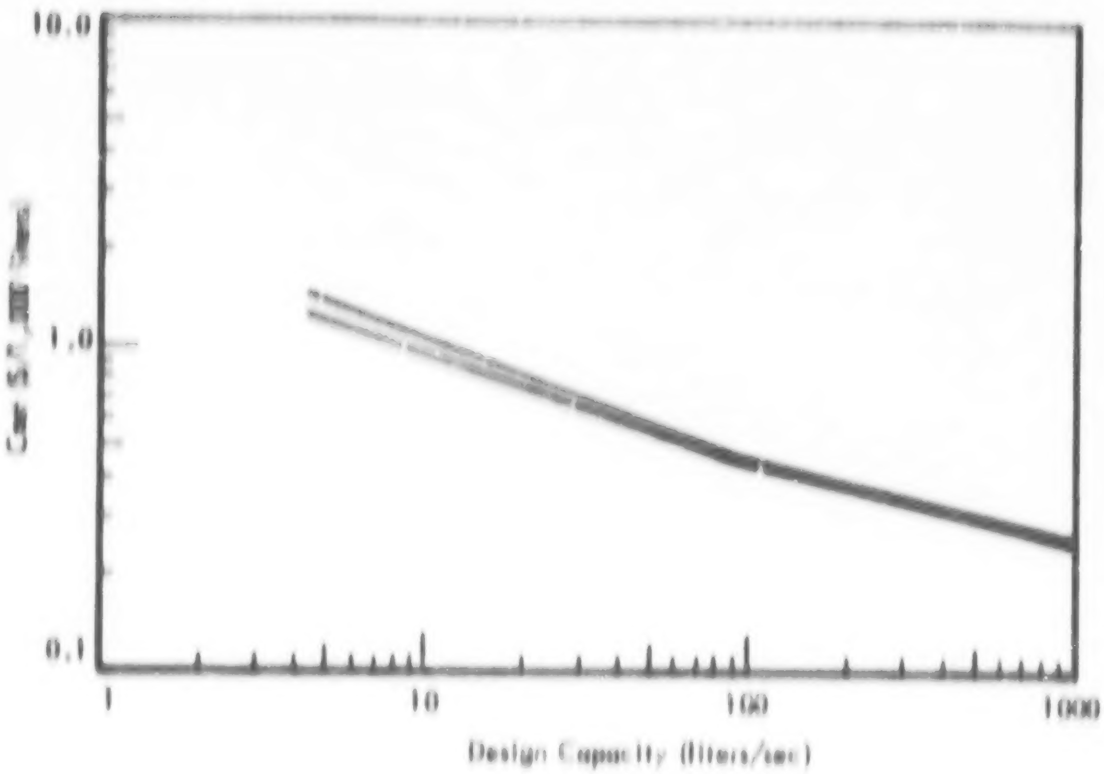
Source: See Figure A-14.

FIGURE IV-28
DISTILLATION BY THE MULTISTAGE
FLASH PROCESS: CAPITAL COST
1974



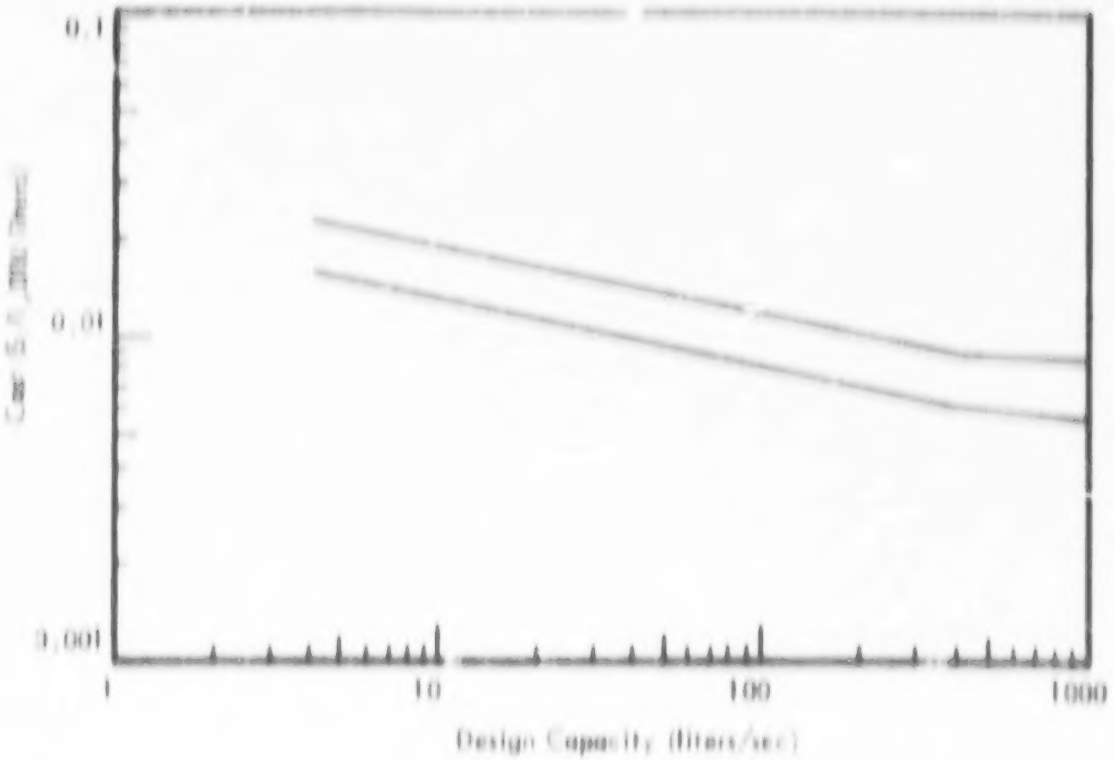
Source: See Figure A-15.

FIGURE IV-29
DISTILLATION BY THE MULTISTAGE
FLASH PROCESS: OPERATION AND
MAINTENANCE COST RANGE
1974



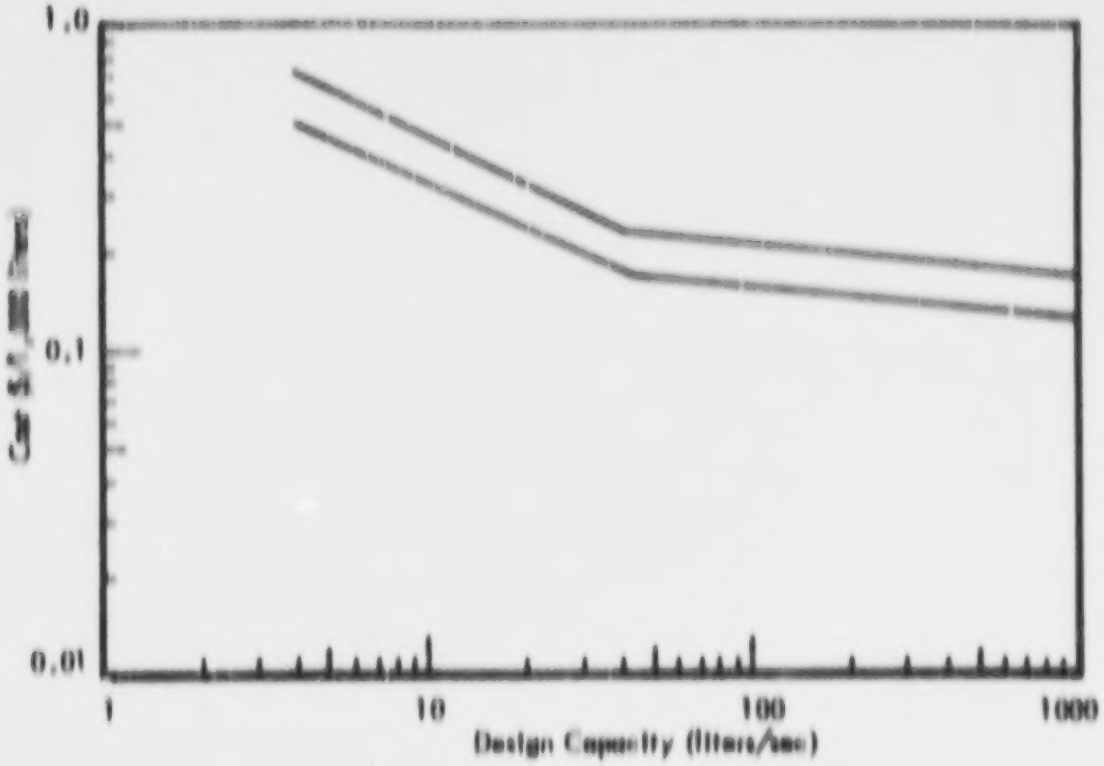
Source: See Figure A-16.

FIGURE IV-30
DISTILLATION BY THE MULTISTAGE
FLASH PROCESS; TOTAL COST RANGE
1974



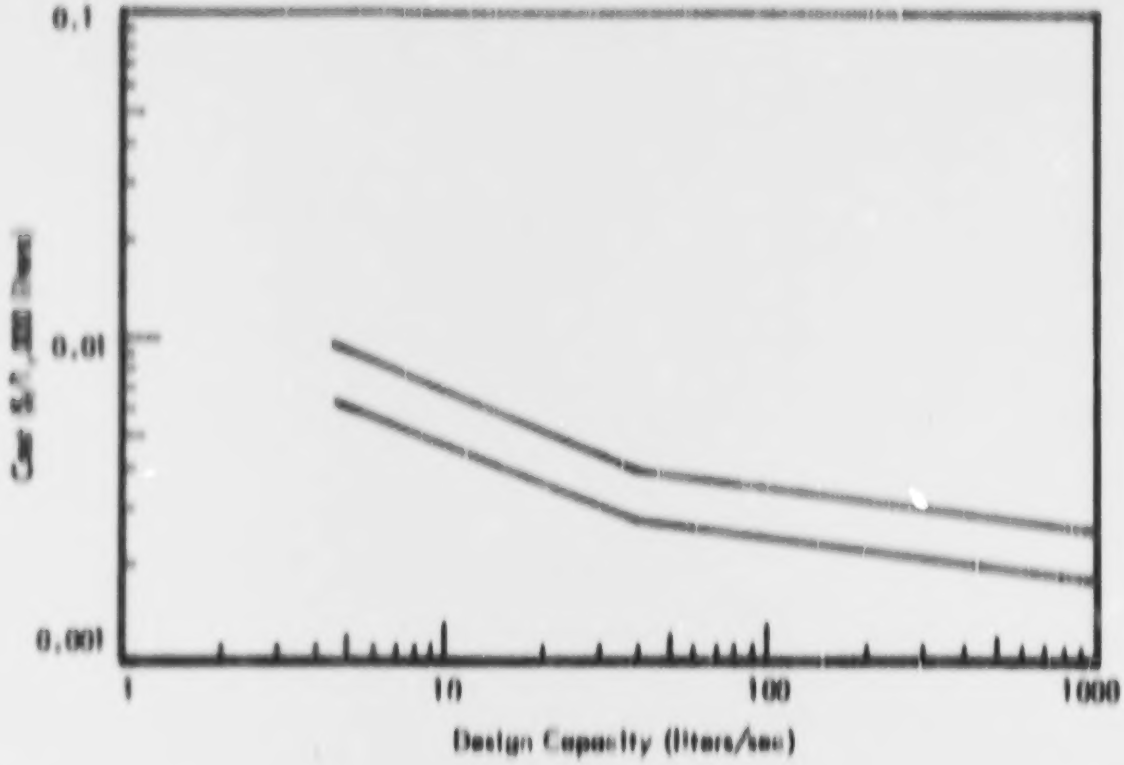
Source: See Figure A-17.

FIGURE IV-[illegible]
DISTILLATION BY THE [illegible]
[illegible] VERTICAL TUBE [illegible],
MULTISTAGE FLASH [illegible]
[illegible]



Source: See Figure A-18.

FIGURE IV-39
DISTILLATION BY THE COMBINED VAPOR COMPRESSION, VERTICAL TUBE EVAPORATOR, MULTISTAGE FLASH PROCESS: OPERATION AND MAINTENANCE COST RANGE
1974



Source: See Figure A-19.

FIGURE IV-33
DISTILLATION BY THE COMBINED VAPOR
COMPRESSION, VERTICAL TUBE EVAPORATOR,
MULTISTAGE FLASH PROCESS: TOTAL COST RANGE
1974

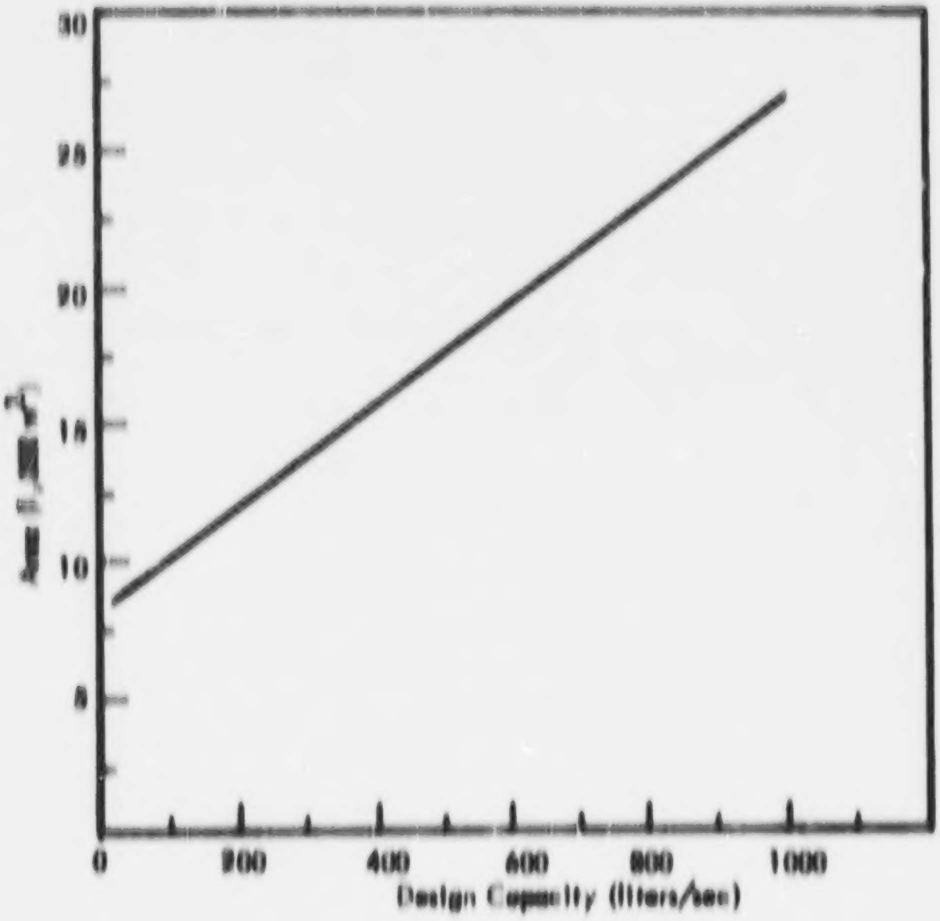


FIGURE IV-34
DISTILLATION BY THE COMBINED VAPOR
COMPRESSION, VERTICAL TUBE EVAPORATOR,
MULTISTAGE FLASH PROCESS:
LAND REQUIREMENTS

Electrodialysis

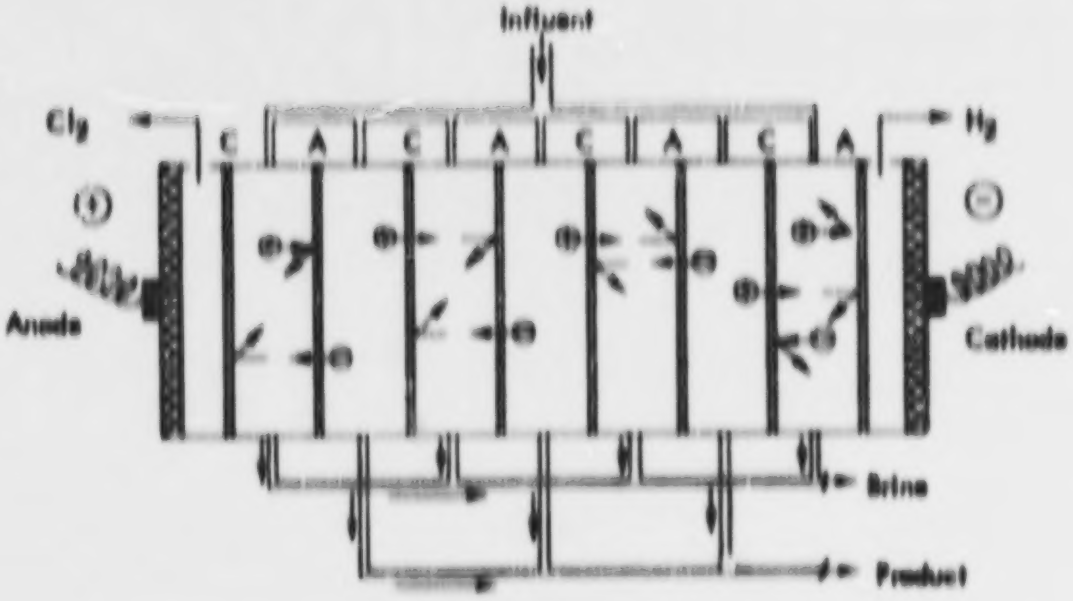
Process Description and Theory.

Electrodialysis (illustrated in Figure IV-35) utilizes electromotive force to transport ionized materials across semipermeable membranes separating solution chambers.[55] An operating electrodialysis unit consists of several chambers (formed by alternating anionic and cationic membranes) situated between two electrodes. Electrodialysis membranes are typically made of conventional ion exchange materials: cationic membranes of sulfonic acid derivatives and anionic membranes of quaternary amine compounds.[55]

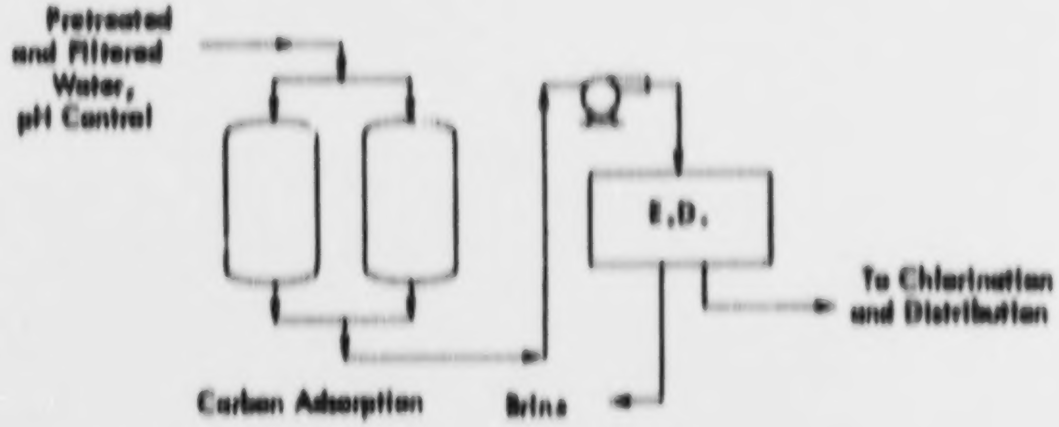
The contaminated influent passes through the chambers and, under the influence of the electromotive forces, the cations move toward the cathode, and the anions toward the anode. The ions are unable to pass through more than one membrane because the alternated anionic and cationic membranes allow the passage of only one type of ion. Consequently, every other chamber contains concentrated waste or purified water. There are several efficiency-reducing problems associated with the process. For instance, the passage of an ion from one chamber to another increases the electrical resistance of that chamber. Eventually, the resistance becomes great enough that no further ion migration is possible. This establishes a lower limit of salinity in the product water. An increase in system operating temperature will overcome this to some extent. Ion buildup at the membrane (concentration polarization) will also increase resistance. Ions which are irreversibly adsorbed by the membranes, or which precipitate as a result of changes in solution composition, can foul the membranes. Finally, the concentrated waste brine must be disposed of.

There are several process configurations possible. The continuous process, particularly suited to large-scale applications, consists of a series of electrodialysis units, each of which receives the effluent from the one preceding. This arrangement achieves greater demineralization than modular units, but does have the problem that changing feed water conditions from one unit to another requires continuous system adjustment. The batch recirculation process achieves the desired effluent quality by pumping a fixed volume of feed from a reservoir, through the electrodialysis unit, and back to the reservoir until the desired effluent quality is achieved. This process requires considerably more hardware in terms of piping, controls, and reservoirs than the continuous process. Higher power is also needed, and since the feed quality is constantly changing, conditions at the membranes vary widely. The process yields a constant effluent quality regardless of changes in influent and membrane properties.

In the feed-and-bleed process, a portion of the effluent water is continuously recycled with the fresh feed, which allows the feed quality to be kept constant. The process does consume considerable power, though, and some fairly sophisticated controls are needed.


Influent
Cl_2
H_2
C
A
C
A
C
A
C
A
⊕
⊖
Anode
Cathode
Brine
Product

A = Anion permeable membrane
C = Cation permeable membrane


Pretreated and Filtered Water, pH Control
E.D.
To Chlorination and Distribution
Carbon Adsorption
Brine

Source: 198.

FIGURE IV-88
SIMPLE ELECTRODIALYSIS SYSTEM

In the internally staged process, the effluent makes several passes in series between a single set of electrodes. It is a continuous process that produces a high degree of demineralization with a constant power demand. This process requires more membrane per unit of product water than the other configurations.

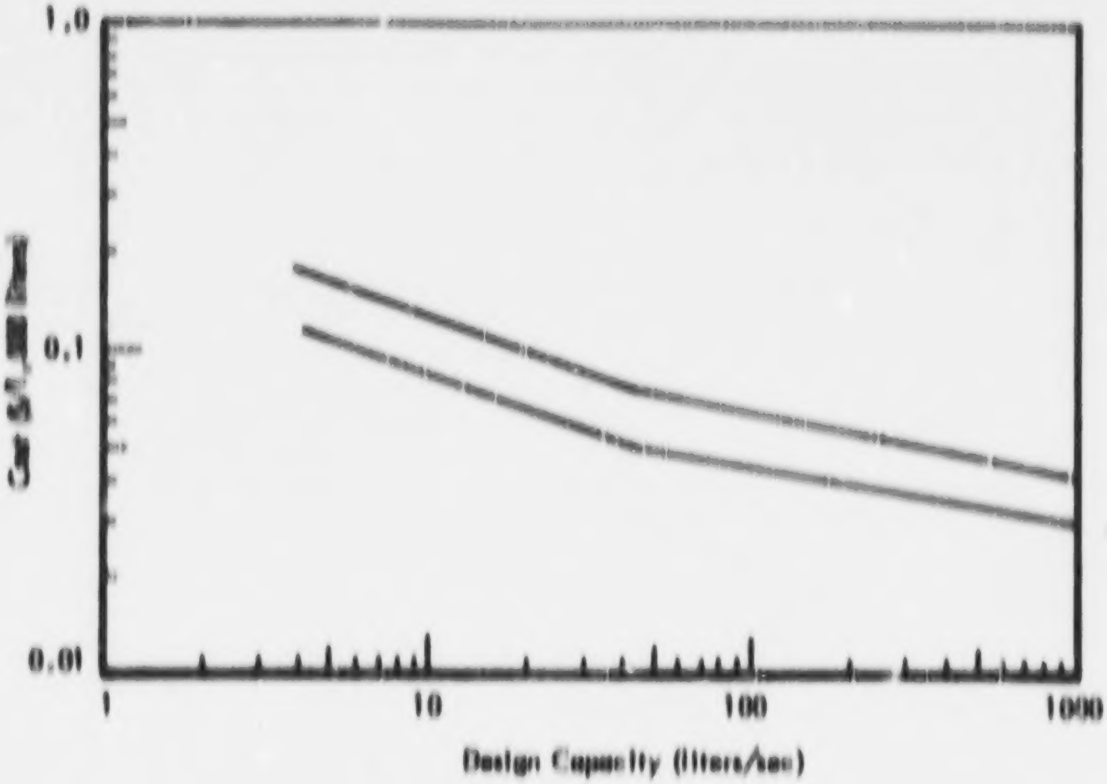
Application.

No data have been found on the use of electrodialysis for treating any of the subject contaminants. The process is used on a moderately large scale for the removal of general dissolved solids, however. The nature of the process dictates that some degree of removal could be accomplished for the eight metallic contaminant species. The magnitude of this removal must remain conjectural, though, until further, more comprehensive data are available. The process description was included only because the process is a valuable addition to the list of potential treatment methods and should not be ignored due to lack of concrete data.

Electrodialysis Costs.

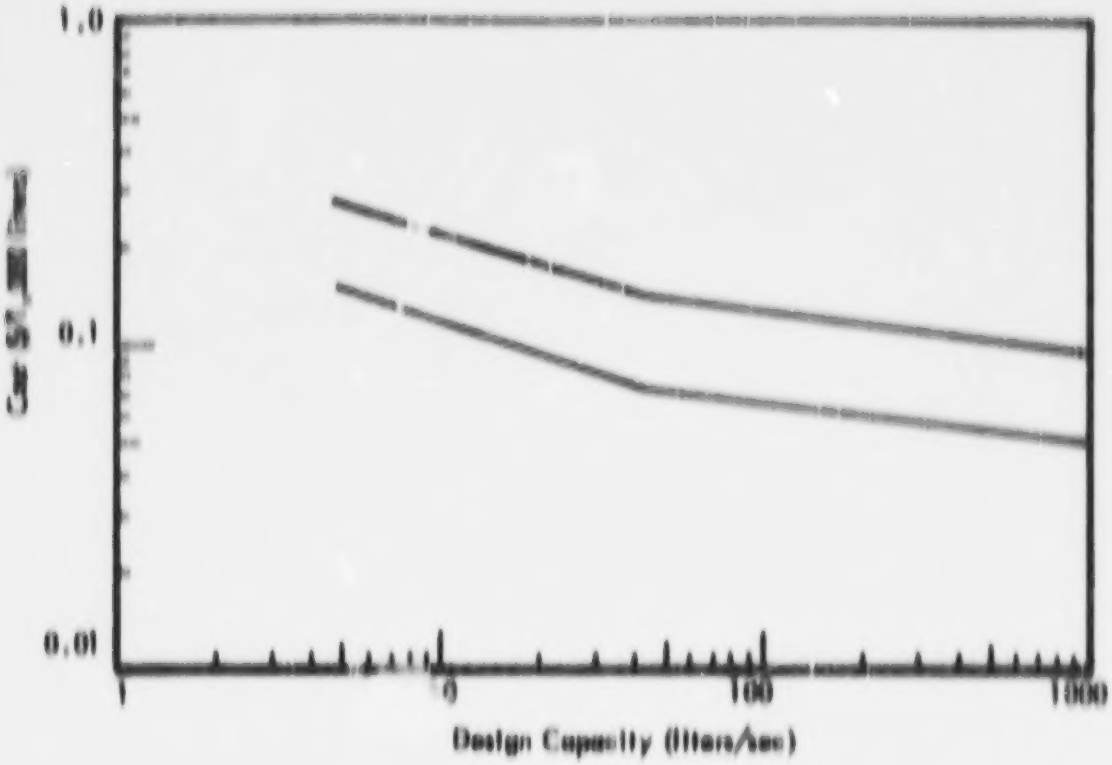
Capital costs (Figure IV-36) were amortized at 7 percent over twenty years. Capital and operation and maintenance (Figure IV-37) costs were derived mainly from information from one manufacturer--Ionics. Two different membrane systems were examined in estimating costs--IM-12 and Brackish Water. The installed cost of IM-12 is about 97 percent higher than the Brackish Water membrane, but operation and maintenance costs are about 81 percent less. Figure IV-38 presents a range for total cost of electrodialysis units.

Membranes can be cleaned by chemical treatment, or reversing current flow. Reverse current flow processes cost about 8 percent less to operate and maintain. Because of the highly competitive nature of electrodialysis research and marketing for water treatment, no information is available on power requirements, costs, or land and space requirements. Land requirements (Figure IV-39) were independently estimated by Ralph Stone and Company, Inc.



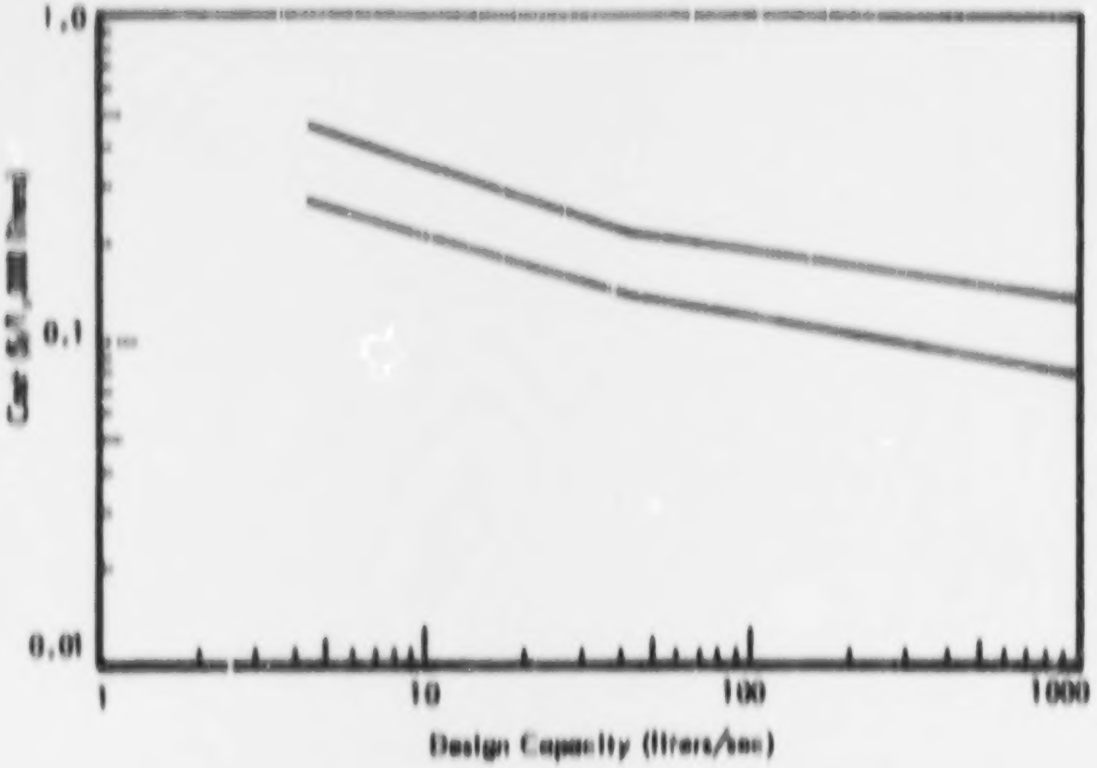
Source: See Figure A-20.

FIGURE IV-86
ELECTRODIALYSIS:
CAPITAL COST RANGE
1974



Source: See Figure IV-21.

FIGURE IV-37
ELECTRODIALYSIS: OPERATION
AND MAINTENANCE COST RANGE
1974



Source: See Figure A-22.

FIGURE IV-38
ELECTRODIALYSIS:
TOTAL COST RANGE
1974

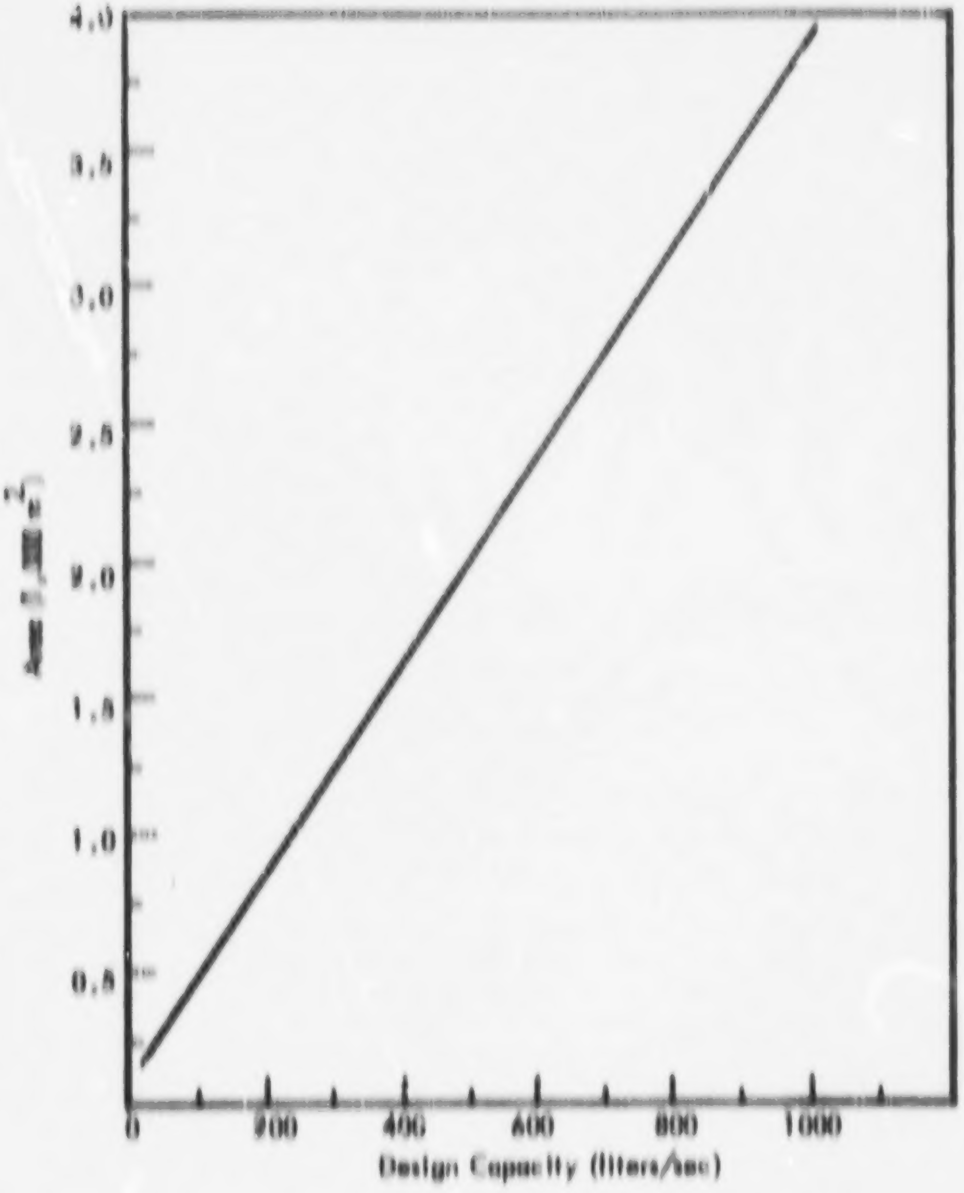


FIGURE IV-39
ELECTRODIALYSIS:
LAND REQUIREMENTS

Source: 198.

Ion Exchange

Process Description and Theory.

Ion exchange is a common type of chemical reaction.[88] For instance, one method of detecting chloride in aqueous solution uses an ion exchange reaction using silver nitrate.

$$M^+Cl^- + Ag^+NO_3^- = M^+NO_3^- + AgCl \quad (1)$$

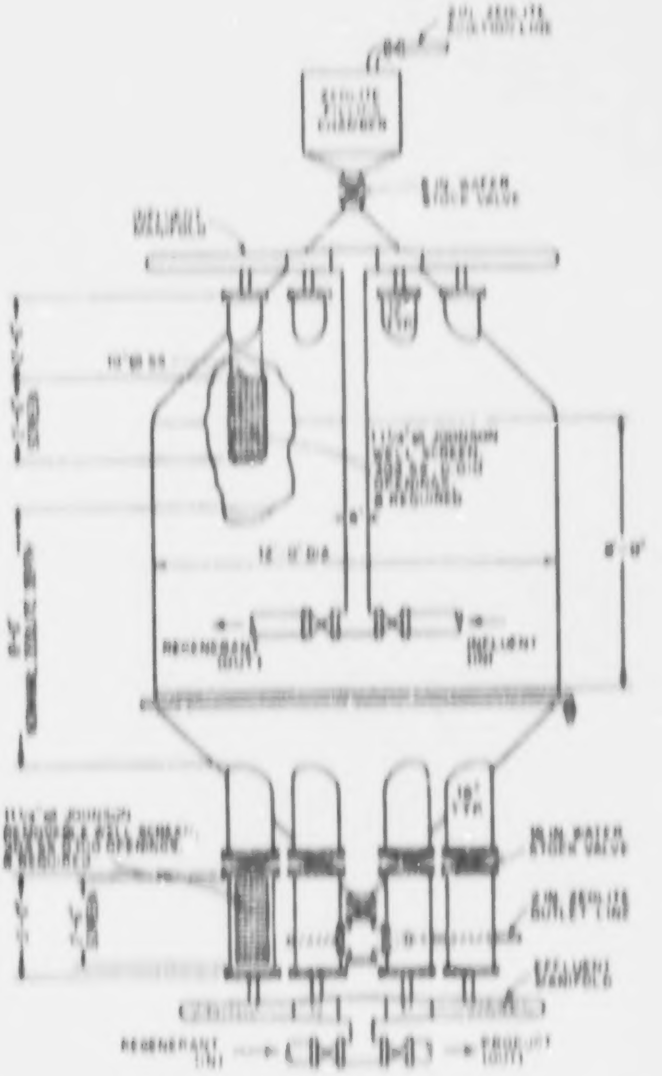
The M and Ag cations have exchanged the chloride and nitrate anions which were their partners in the original solutions. Recently, the ion exchange technique has been associated with the process of causing water to flow through beds or columns of zeolite type materials. An ion exchange material is a solid consisting of a molecular network, usually an organic polymer or inorganic silicate, containing electrically charged sites of one particular charge sign and mobile ions of the opposite sign. In a cation exchange resin, the immobile molecular network is anionic; the mobile ions are cations. In anion exchanges, the molecular charges or signs are reversed.

Ion exchange is used to substitute one ion for another in a solution. For example, if water containing Ca^{+2} ions flows through a column of cation exchange material containing Na^+ ions as the mobile groups, displacement occurs, with the Ca^{+2} binding to the molecular network and Na^+ ions appearing in the effluent. This particular process is the one used to convert hard water to soft water.

The nature of the ionic groups on the ion exchanger material largely determines the behavior of the ion exchanger. The group type affects both the ion exchange equilibrium and ion selectivity; the total number of groups per unit volume of resin dictates the exchange capacity.

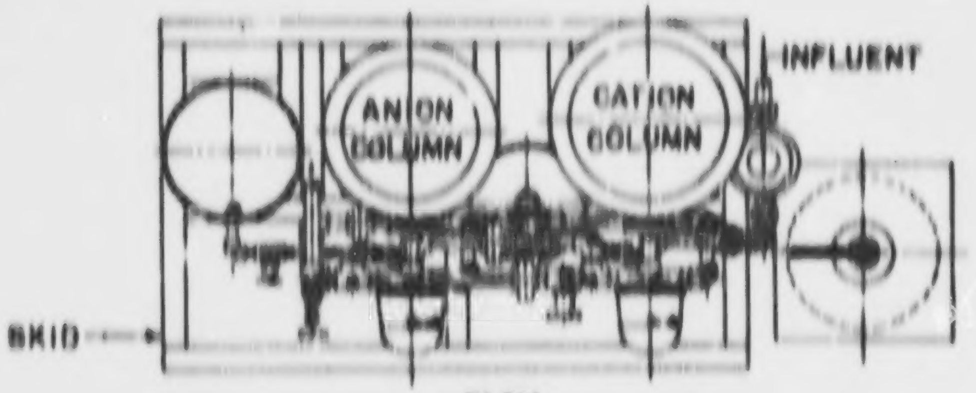
There are two main operating modes for ion exchange: batch and column applications. Batch operation involves adding a quantity of ion exchange resin to water to be treated and mixing the slurry until a condition of equilibrium is attained for the ion exchange solution. This mode of operation is used for ionic solutions with high selectivity under the equilibrium conditions. Furthermore, the ion being released by the resin should be relatively harmless or easily removed (e.g., by precipitation from water). Column operation (see Figures IV-40 through 42) is, strictly speaking, a series of batch operations. In practice, column operation involves passing water through a packed column or open bed filled with ion exchange resin. It can be applied for ions with low selectivity toward the resin, and requires that the water be free of settleable and suspended solids before it flows through the column (to prevent bed clogging and fouling).

There are several types of ion exchangers available--strongly and weakly acidic cation exchangers and strongly and weakly basic anion exchangers. Strongly acidic cation exchangers include those resins containing functional acid groups such as sulfonic ($R\text{-}SO_3H$) or sulfuric ($R\text{-}OSO_3H$). Weakly acidic cation exchangers include those resins containing functional weak acid groups such as phenolic ($R\text{-}C_6H_4\text{-}OH$), carbonic ($R\text{-}OCO_2H$), or carboxylic ($R\text{-}COOH$). Strongly basic anion exchangers contain such functional groups as primary amine ($R\text{-}NH_2$), secondary amine ($R\text{-}R'NH$), and tertiary amine ($R\text{-}R'_2N$).

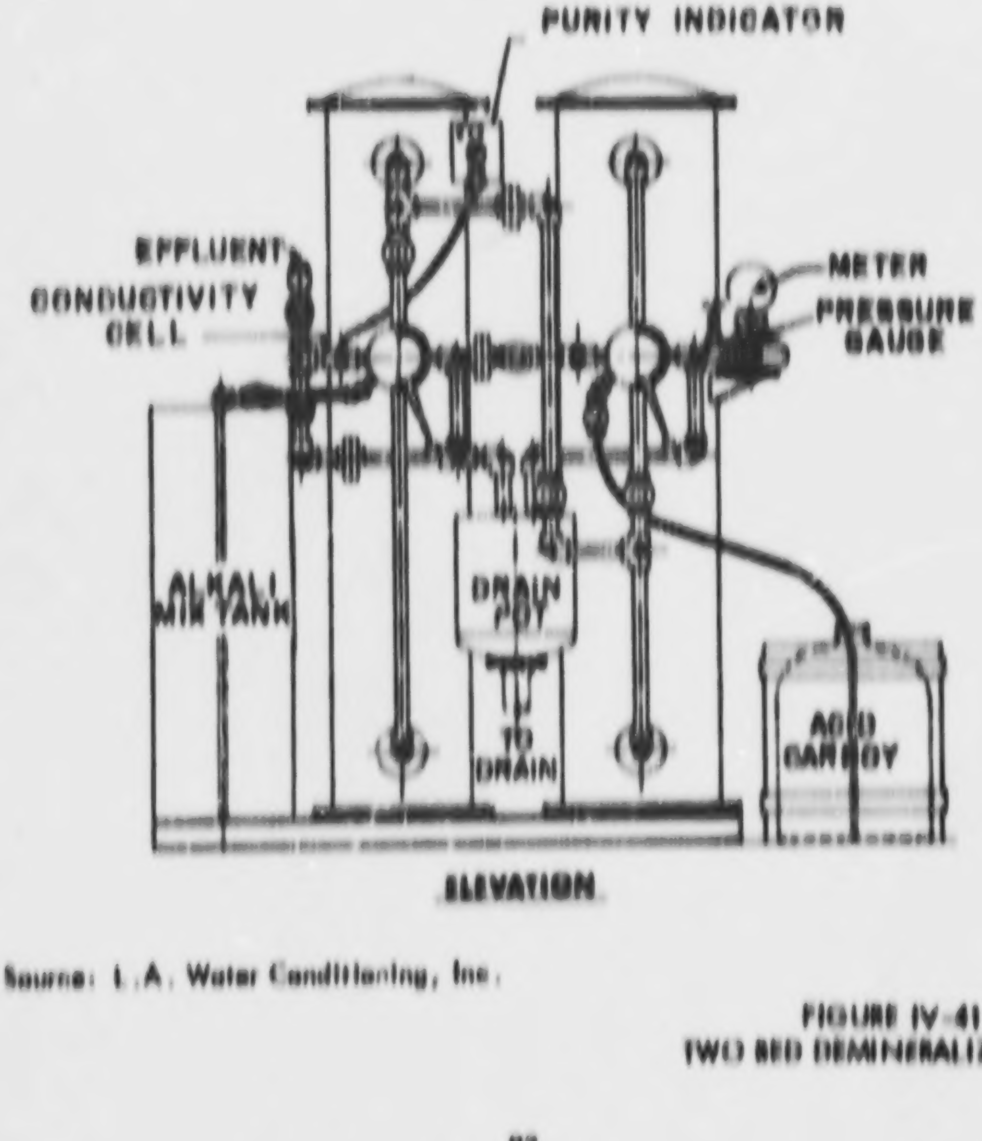


Source: 196.

FIGURE IV-40
TYPICAL ION EXCHANGE BED


INFLUENT
ANION COLUMN
CATION COLUMN
SKID

PLAN

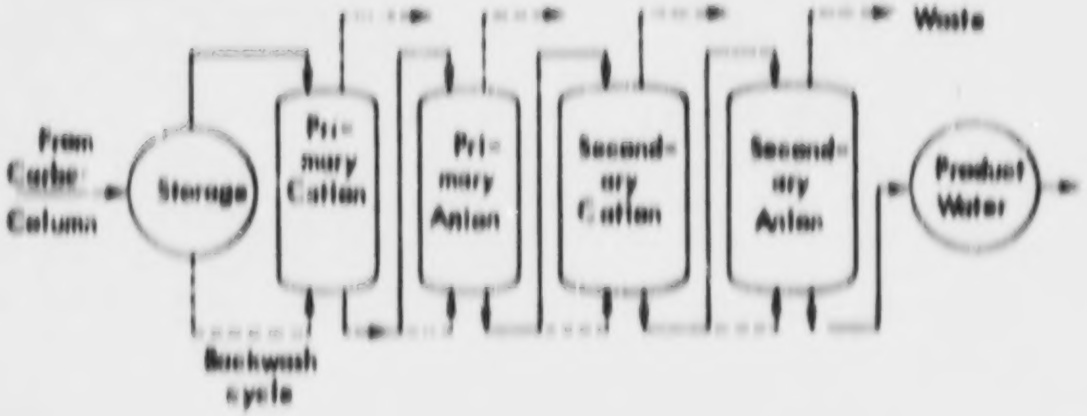

PURITY INDICATOR
EFFLUENT CONDUCTIVITY CELL
METER
PRESSURE GAUGE
ALKALI MIX TANK
DRAIN POT
TO DRAIN
ACID CARBOY

ELEVATION

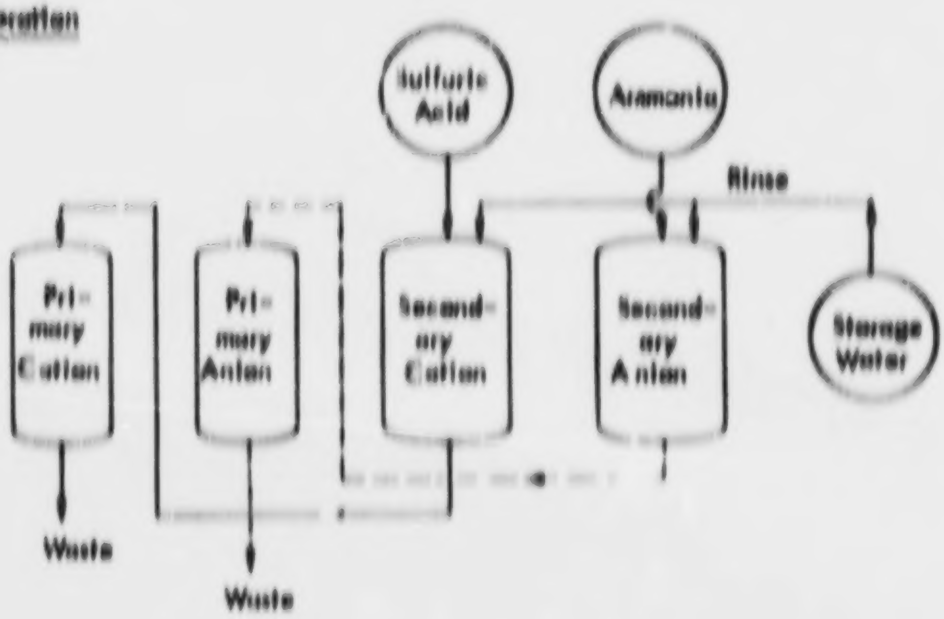
Source: L.A. Water Conditioning, Inc.

FIGURE IV-41
TWO BED DEMINERALIZER

Treatment


Waste
From Carbon Column
Storage
Primary Cation
Primary Anion
Secondary Cation
Secondary Anion
Product Water
Backwash cycle

Regeneration


Sulfuric Acid
Ammonia
Rinse
Primary Cation
Primary Anion
Secondary Cation
Secondary Anion
Storage Water
Waste
Waste

Source:45.

FIGURE IV-42
ION EXCHANGE
COLUMN SERIES

Weakly basic anion exchangers contain functional groups derived from quaternary ammonium compounds, such as $R-R'_3N^+OH^-$. R is the organic network of the resin and R' is an organic radical such as an alkyl group.

The efficiency of an ion exchange unit depends on the characteristics of the exchange material, the operating parameters (temperature, pressure, flow rate, solution pH, etc.), and whether there is one column or several operated in series. The various types of exchange resins and the various functional groups strongly affect the selectivity of a resin and its affinities for different ionic species. For instance, to cite a rather obvious example, an anion exchange resin could not be used to remove cations from solution. Any attempt to do so would be completely inefficient. The operating parameters generally affect the equilibrium constants and the speeds of reaction. Consequently, a change in any of these parameters would change the efficiency of the unit.

Ion exchange resins have a finite capacity: as the exchange sites become filled with contaminant ions, the operating efficiency will eventually fall below acceptable levels. The saturated resin must then be removed from operation and regenerated. The details of regeneration vary depending on the resin and the contaminant ions but, in general, regeneration involves the removal of the contaminant ion and its replacement by mobile ions of the same type as were originally on the resin prior to its use. This is accomplished by flooding the resin with an extremely concentrated solution of the original ion, reversing the equilibrium, and exchanging the ions again. The resulting concentrated waste brine of the contaminant ion must be disposed of.

Application.

Ion exchange is most commonly used to soften or demineralize water, to concentrate and recover useful by-products from industrial wastes, or in analytical separations. For instance, a simple demineralizer is the two-bed batch operation. This consists of a cation and an anion exchanger operated in series. The contaminant cations and anions are removed and replaced by hydrogen and hydroxide ions. The exchangers are regenerated with concentrated strong acid and concentrated sodium hydroxide, respectively.

All eight of the subject metal contaminants can be removed to some degree by ion exchange. Nearly all of the available data relate to bench-scale experiments, however. Antimony was removed from solution using Amberlite CG-400, 100-200 mesh, 8 percent cross-linked. This is a strongly basic, polystyrene type anion exchange resin. In the laboratory experiments, 15 mg of antimony (as antimonite) was completely removed from acid solution using 10 g of resin.[97]

Beryllium can be removed by Dowex 50 (Ion X, 200-400 mesh), a strongly acidic, polystyrene-type cation exchange resin. Laboratory experiments indicated a resin requirement of 0.35g resin per milliequivalent of cation. Tests on slightly alkaline solutions containing 8.4 and 10.5 mg Be yielded effluents of 0.6 and 0 mg Be, respectively.[110]

Cobalt and nickel can be removed with Wofatit MC 50 chelating ion exchange resin. In laboratory tests, amounts in raw water up to 12 mg of each were removed completely.[98] Lithium can be removed from solution with an ion sieve cation exchange resin, such as ISM-2. No data were available on conditions or removal efficiencies, but the resin is question has shown a very high selectivity for lithium over other metals and quantitative removals can be expected.[101]

Molybdenum can be removed by several resins, but almost always as the molybdate anion. De-Acidite FF, a strongly basic, polystyrene type anion exchange resin can be used to remove molybdenum from acid (pH=2-4) solutions. In tests conducted with 25 ml columns of resin, 95 percent of the molybdenum was removed from influent solutions containing up to 2.75 mg/liter Mo.[101] Removal was even better using DEAE (diethylaminoethyl) cellulose in the SCN form. In actual tests, passing 10 ml samples at a pH of 3 and molybdenum concentrations of 0.1 to 5 mg/liter through 1g samples of the cellulose achieved 98 + percent removal.[97]

Tungsten can also be removed as the tungstate anion using DEAE cellulose in the SCN form. The actual tests, which consisted of passing 10 ml samples at a pH of 7 and tungsten concentrations of 0.004 to 2 mg/liter through 1g samples of the cellulose, achieved 98 + percent removal.[97]

Vanadium can be removed as the vanadate anion using anion exchange resins. Using De-Acidite FF, up to 96 percent of the vanadium can be removed from acid solutions containing 1.5 to 5 mg V when passed through 25 ml columns of the resin.[101] Slightly better results have been achieved using Dowex 1-X8, a strongly basic, polystyrene type anion exchange resin, in the SCN form. In the actual tests, two liters of sample containing 11.16 mg of vanadium were acidified, 15.2 g of ammonium thiocyanate were added, and the solution was passed through 5 g of the resin. The effluent contained 0.30 mg of vanadium.[99]

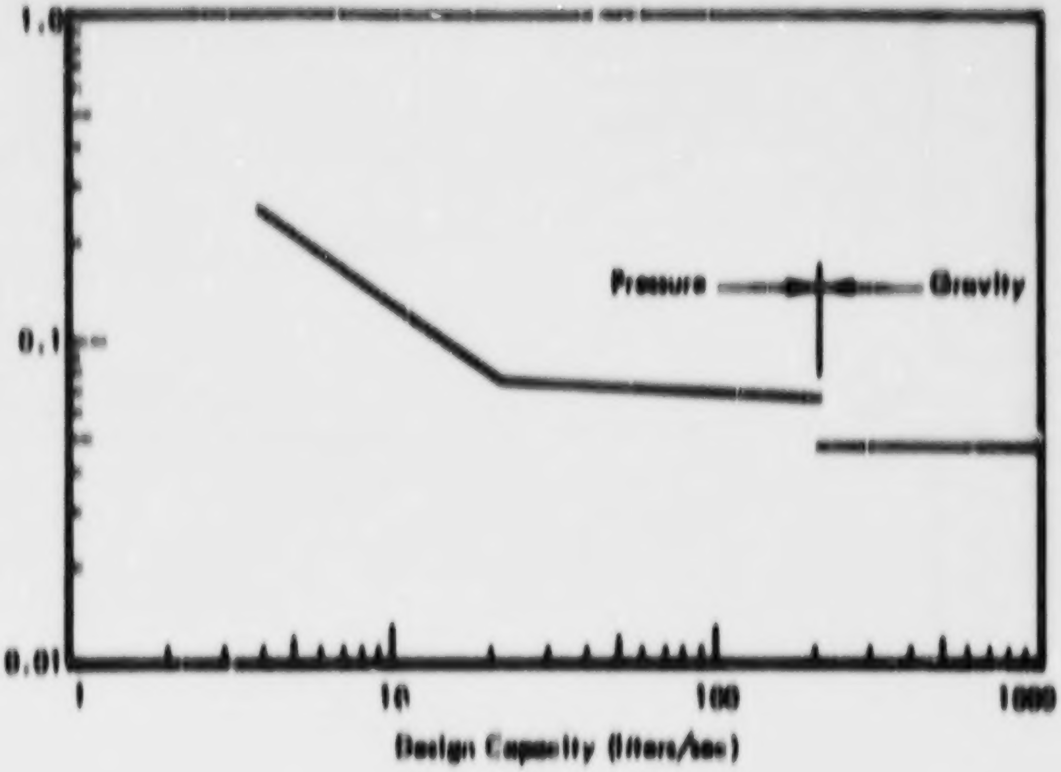
It should be pointed out that these are not the only resins available that will accomplish these removals. Some of the resins mentioned here will probably also remove others of the subject metals. Unfortunately the data, if existing, were not located.

Some work has also been done on removing insecticides using anion exchange. Experimental data are incomplete and inconclusive, but the limited tests conducted so far have yielded very good removal efficiencies.[98]

Ion Exchange Costs.

Costs were estimated over the range of 1 to 1,000 liters/second based largely on manufacturers' cost estimates for various size water treatment plants. Capital costs were amortized at 7 percent over a 20 year useful life. Annual maintenance costs were estimated at 3 percent of capital costs. Resin costs were estimated at 8 percent of original capital costs. Resin regenerants used were H_2SO_4 at $0.04 per kg and NaOH at $0.21 per kg. Amounts of regenerants per regeneration were estimated using a $CaCO_3$ contaminant model. Frequencies of regeneration were based on estimated maximum and minimum concentrations derived from the literature. For the resin specific for lithium removal, a concentration range of 0.00008 to 0.1 mg/liter was used. The resins for tungsten, molybdenum, cobalt, and nickel are limited primarily to trace heavy metals and a range of 0.01 to 10 mg/liter was used. The resins for beryllium, antimony, and vanadium are non-specific, so a range of 1 to 250 mg/liter was used.

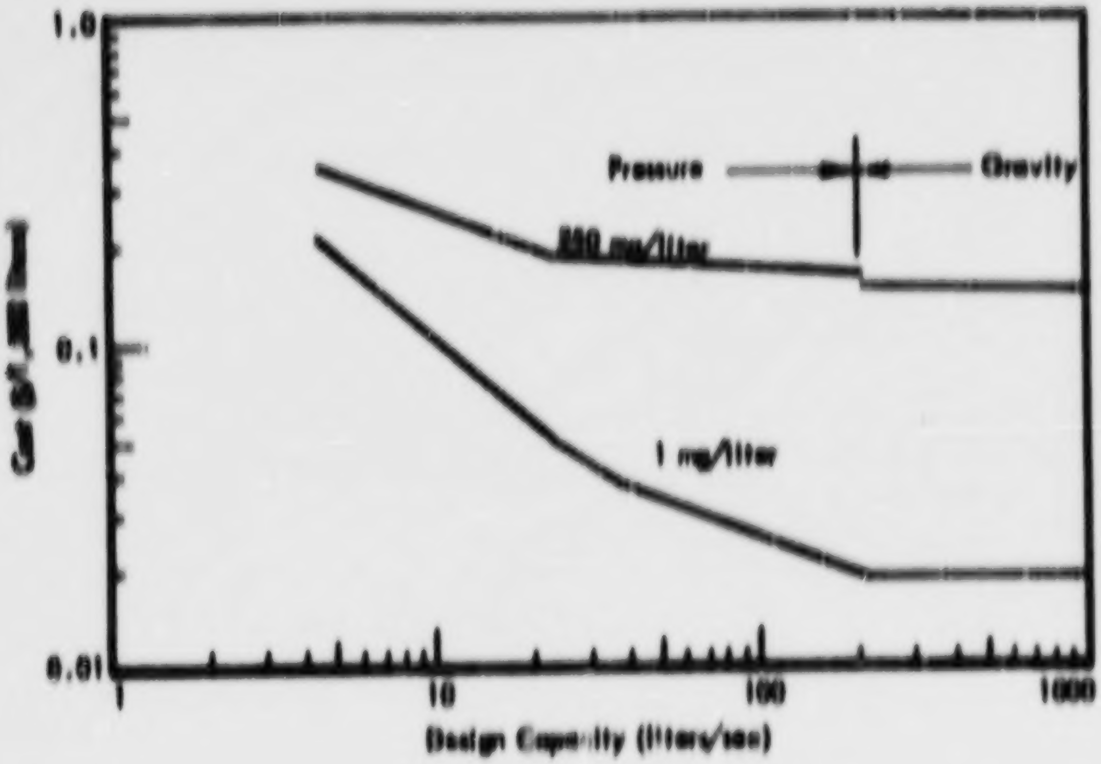
Prefabricated (pressure) ion-exchange units were utilized up to about 200 liters/sec and field-built, open-type (gravity) units were utilized thereafter. Salaries were assumed constant. Figure IV-43 presents capital costs for all elements. Figures IV-44 through IV-53 present (1) operation and maintenance and (2) total costs for antimony and vanadium, beryllium, cobalt and nickel, lithium, and tungsten and molybdenum. Figure IV-54 presents land requirements.



Source: See Figure A-88.

FIGURE IV-48

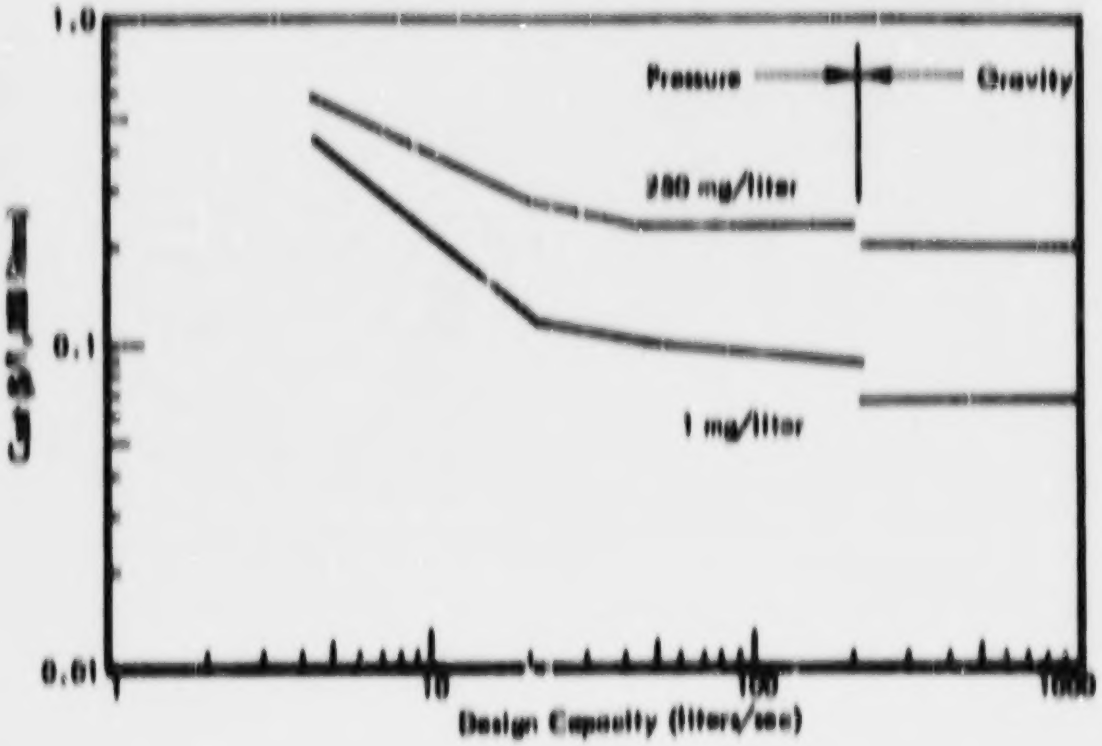
ION EXCHANGE FOR ALL ELEMENTS:
CAPITAL COST
1974



Source: See Figure A-84.

FIGURE IV-44

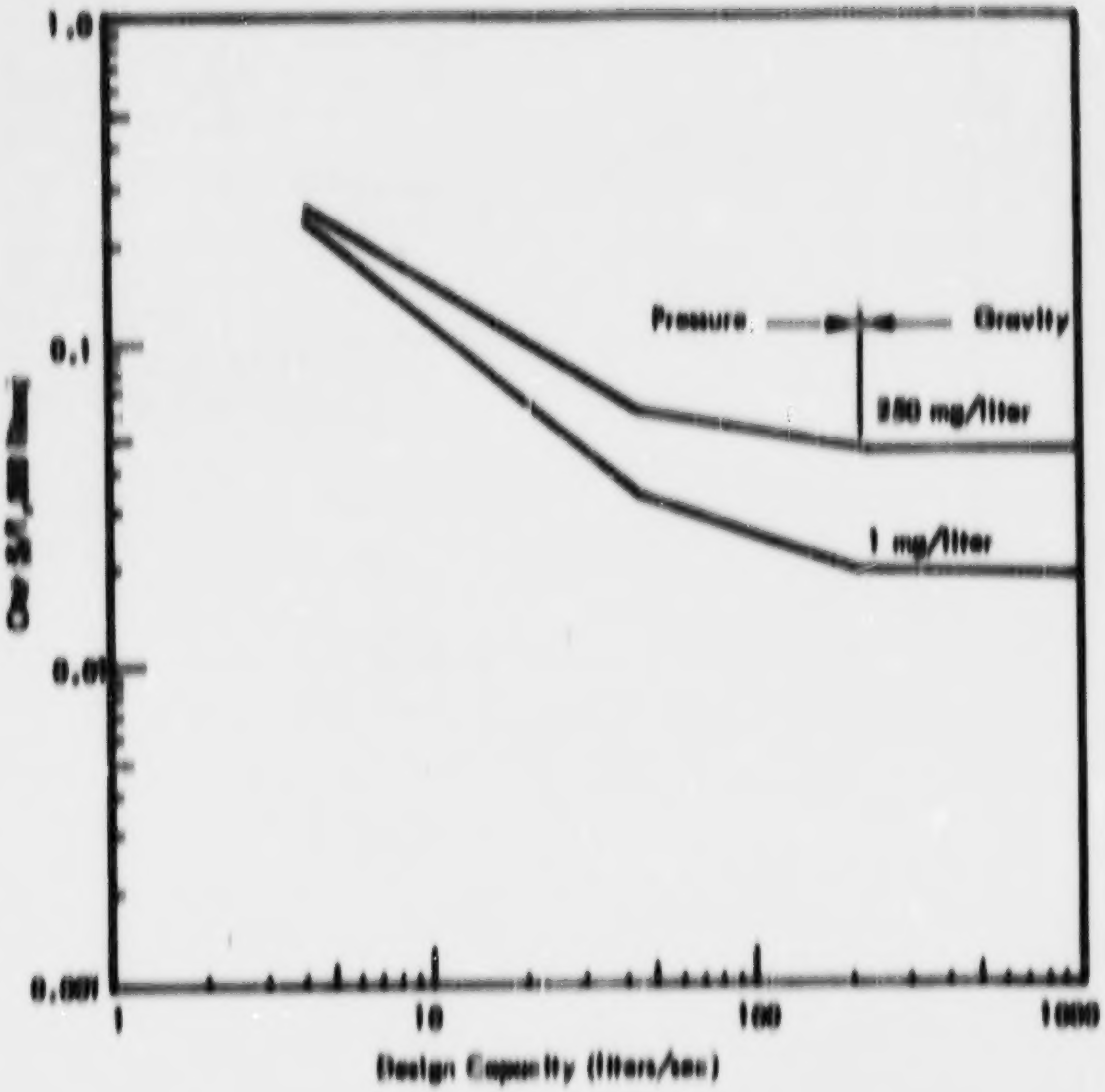
ION EXCHANGE FOR
ANTIMONY AND VANADIUM:
OPERATION AND MAINTENANCE COST RANGE
1974



Source: See Figure A-25.

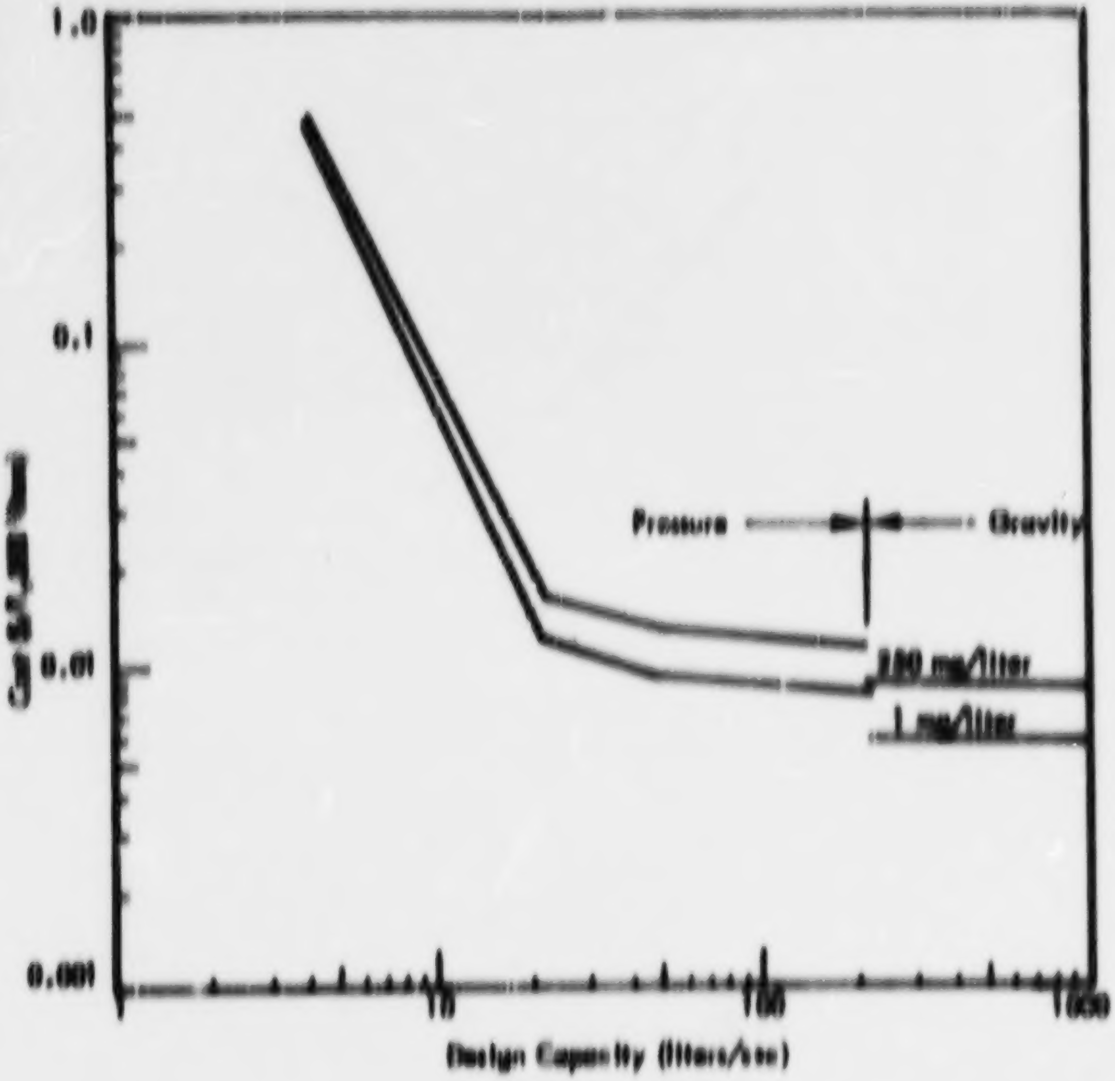
FIGURE IV-45

ION EXCHANGE FOR
ANTIMONY AND VANADIUM:
TOTAL COST RANGE
1974



Source: See Figure A-26.

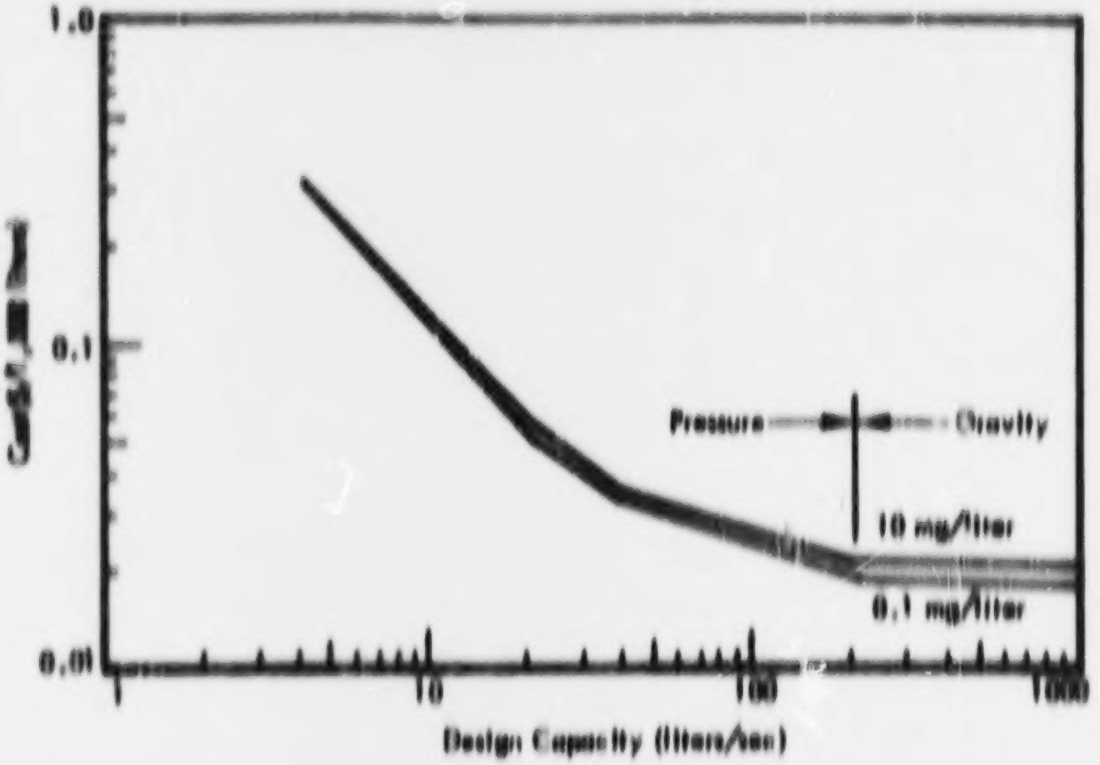
FIGURE IV-46
ION EXCHANGE FOR
BERYLLIUM: OPERATION
AND MAINTENANCE COST RANGE
1974



Source: See Figure A-67.

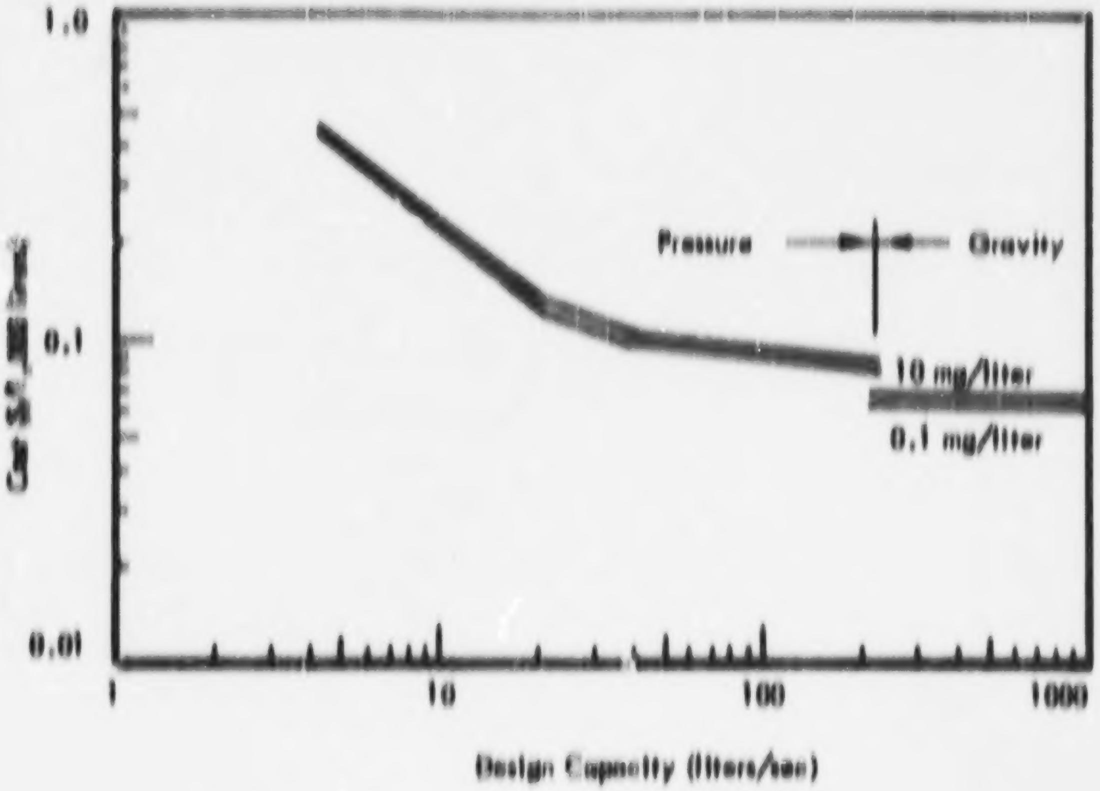
FIGURE IV-47

ION EXCHANGE FOR
BERYLLIUM, TOTAL COST RANGE
1974



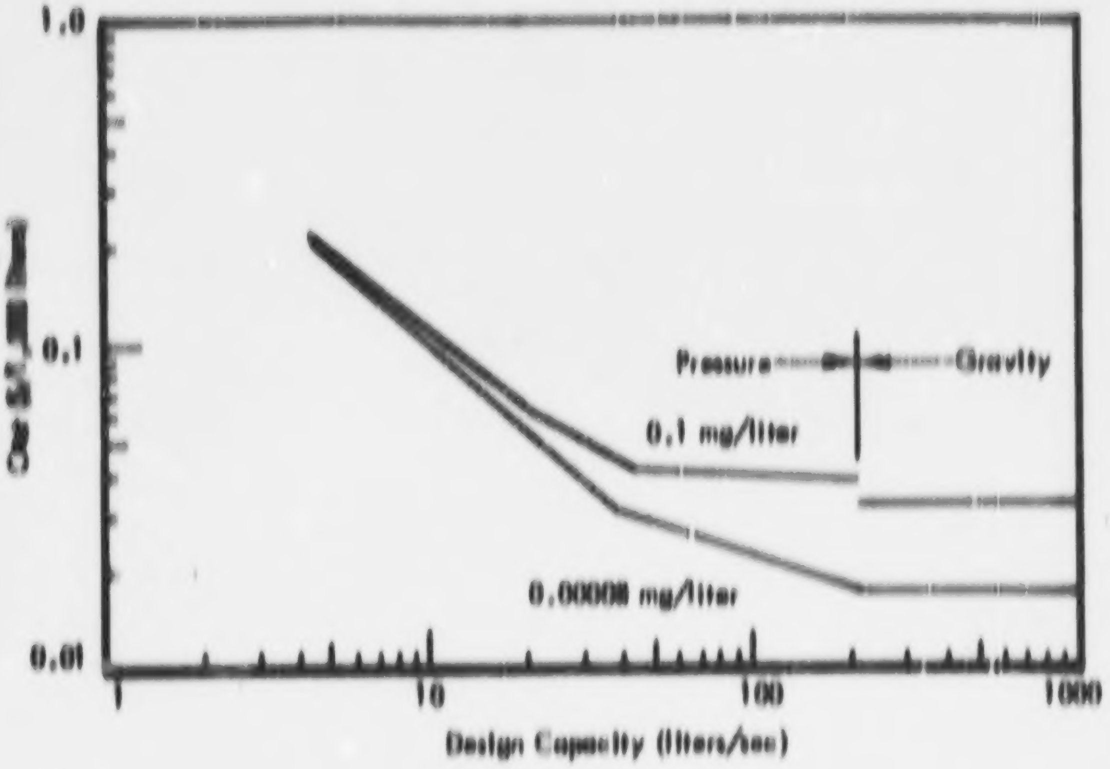
Source: See Figure A-88.

FIGURE IV-48
ION EXCHANGE FOR
COBALT AND NICKEL OPERATION
AND MAINTENANCE COST RANGE
1974



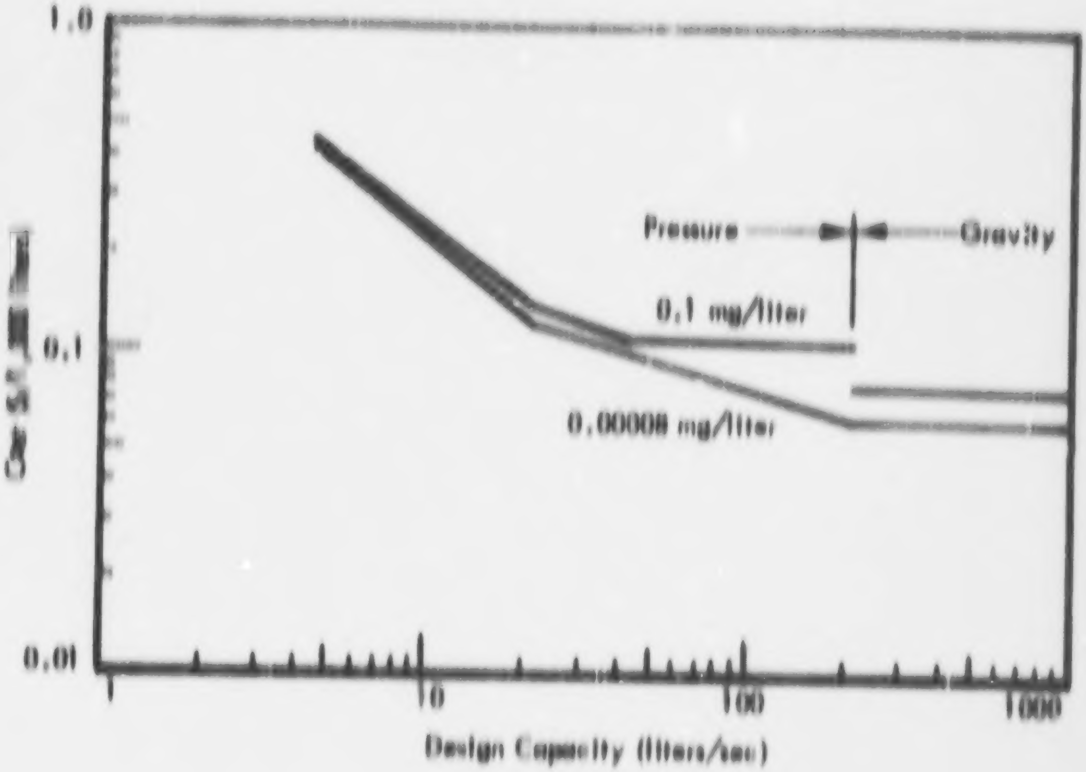
Source: See Figure A-89

FIGURE IV-49
ION EXCHANGE FOR
COBALT AND NICKEL,
TOTAL COST RANGE
1974



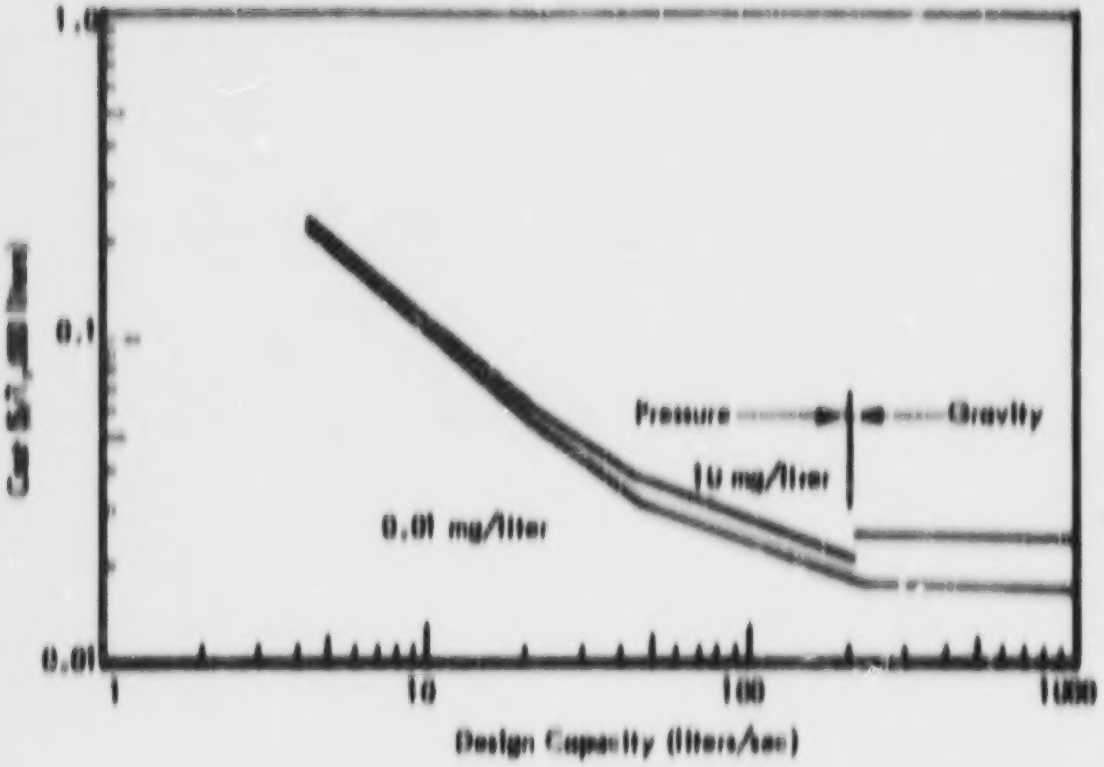
Source: See Figure A-30.

FIGURE IV-80
ION EXCHANGE FOR
LITHIUM: OPERATION
AND MAINTENANCE COST RANGE
1974



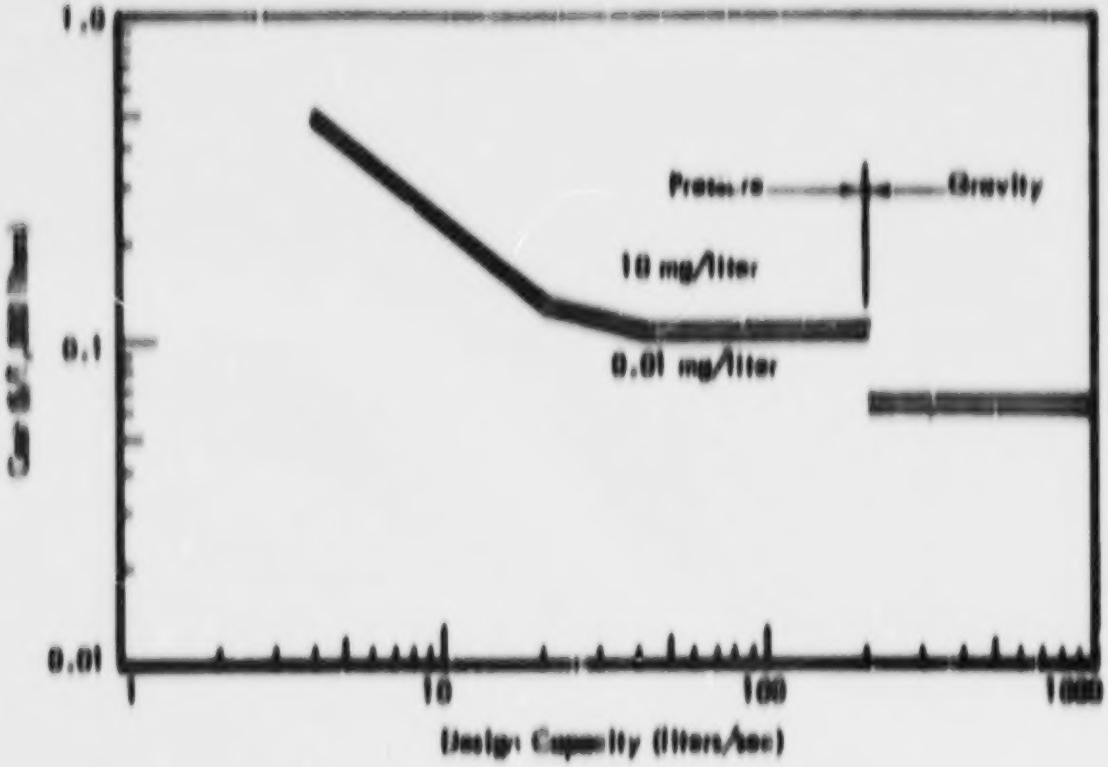
Source: See Figure A-31.

FIGURE IV-31
ION EXCHANGE FOR
LITHIUM: TOTAL COST RANGE
1974



Source: See Figure A-32.

FIGURE IV-32
ION EXCHANGE FOR TUNGSTEN
AND MOLYBDENUM: OPERATION
AND MAINTENANCE COST RANGE
1974



Source: See Figure A-33

FIGURE IV-33
ION EXCHANGE FOR
TUNGSTEN AND MOLYBDENUM,
TOTAL COST RANGE
1974

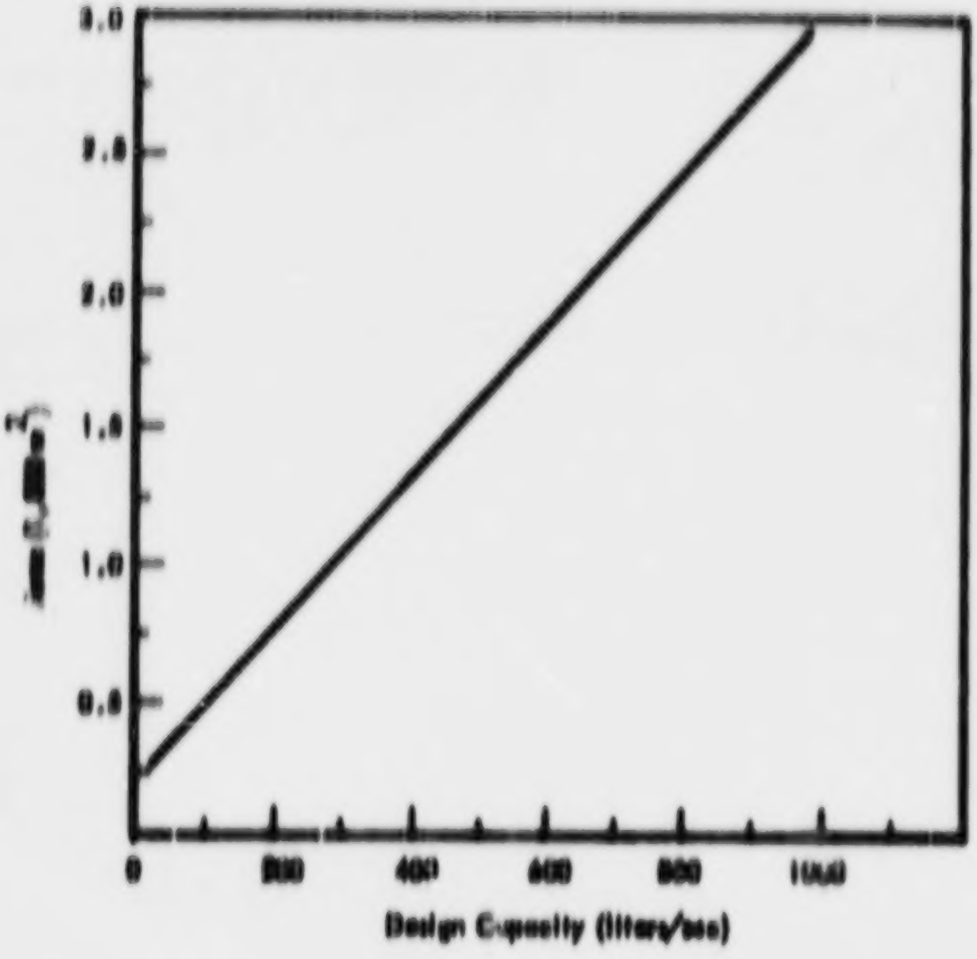


FIGURE IV-84

ION EXCHANGE:
LAND REQUIREMENTS
FOR ALL ELEMENTS

Source: 198.

Radiochemical Degradation

Process Description and Theory.

A large number of organic compounds are susceptible to degradation by electromagnetic radiation of certain wavelengths. Each wavelength possesses energy which can be used to overcome chemical bonding energies and break down molecules into stable compounds or unstable atoms or ions. The unstable radicals so produced can react with undecomposed molecules and break them down. In water, for instance, gamma radiation will produce a series of ionizing reactions among organic compounds and will react with water to produce unstable atoms and free radicals which will also react with the organic compounds in solution. End products usually consist of smaller, simpler organic compounds which can be subjected to conventional treatment.

Among the high energy radiations which can be or have been employed in waste treatment studies are ultraviolet, gamma radiation, and X-rays. Long wavelength, low energy microwaves have also been studied and show some promise. Microwave degradation is a result of vibrational and heat energy phenomena and is quite different from other radiation treatment methods.

In practice, all radiation treatment methods are expensive and exhibit a host of operational difficulties. They are, however, remarkably effective in treating some refractory organic wastes, and they have an advantage in that no material is added to the water which must be removed later with coincident sludge disposal problems.

Ultraviolet. Ultraviolet irradiation is perhaps the simplest of the radiation processes. It has been used at pilot-plant scale as a disinfectant and has proven to be fairly effective. The most common source of ultraviolet light of 2000-3000 Å is low-pressure mercury vapor lamps. For large-scale operation, a more efficient source is needed. Since normal glass does not transmit ultraviolet, windows for the ultraviolet must be of quartz or special UV-transmitting glass.

In practice, only shallow water can be treated by ultraviolet, since it normally is capable of only a few inches penetration in water. This necessitates using either a very shallow water trough below a battery of lamps or a series of lamps immersed in the water to be treated. The addition of certain energy-attenuating catalysts, however, can increase effective penetration in clear water to about three feet. Turbidity and color can seriously limit the effectiveness of ultraviolet treatment as they will block the radiation. Consequently, turbid or colored waters require some pretreatment prior to ultraviolet treatment. Conventional coagulation/sedimentation would probably be sufficient.

Ultraviolet radiation reacts with water to produce hydrogen peroxide (H_2O_2), an effective oxidant of organic compounds. The reaction is not a fast one, however, and the use of a catalyst to speed it up is advisable. The more common ones are ZnO or TiO_2 "sands" in the bottom of the treatment chamber.

Ultraviolet treatment can completely eliminate carbamates from drinking water.[89] Removal efficiencies for chlorinated hydrocarbons vary, depending on the structure of the compound. For instance, after one hour of treatment, Aldrin is reduced by 40 percent whereas Endrin and Dieldrin are reduced by only about 10 percent.[89] Dieldrin tends to isomerize when treated with ultraviolet. Organic phosphorus compounds are also reduced by ultraviolet, but data on reduction efficiencies are unavailable.

Gamma Radiation. Gamma irradiation has only been examined on a laboratory scale and consequently no data are available for pilot or full-scale plants. The current source for gamma radiation is cobalt-60. In the future, nuclear reactor wastes could conceivably be used instead of Co-60. In practice, a concentric cylinder design is used (see Figure IV-60). The innermost cylinder contains the radiation source material. The water to be treated is passed through a cylinder surrounding this core. The whole configuration can be easily shielded. Suspended solids must be removed prior to treatment because of the danger of producing radioactive particles in the water. Similarly, effluent from the gamma treatment column must be monitored and filtered to remove any radioactivity which might have gotten through.

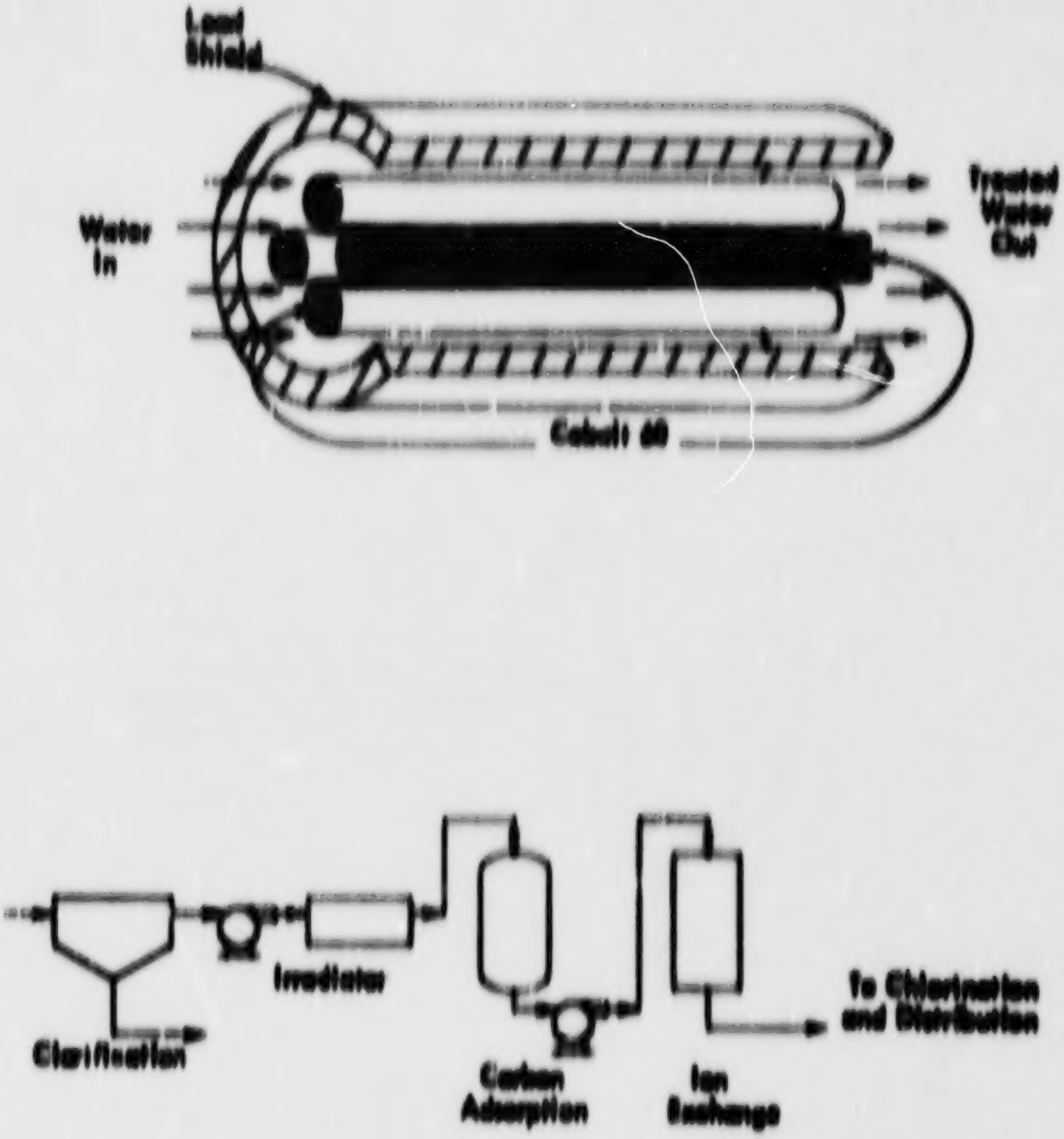
Protecting the health and safety of the operator is the major problem with the use of gamma radiation. Gamma radiation is extremely hazardous and the utmost care must be exercised in its use. Special shielding for operators and equipment is required. There is the added problem of public acceptance of drinking water which has been exposed to radioactivity.

Gamma radiation has been used to remove PCB's from water on a laboratory scale. Tests on 50 and 100 µg/liter PCB solutions yielded peak removal efficiencies of 95-98 percent at a pH of 8 with a gamma dose of 10.0 M rad.[131]

Microwave. The third type of radiation under discussion, microwave radiation, has thus only been examined at the laboratory level, and then only on simple alcohols, ketones, and ethers. Furthermore, the tests were performed on gaseous samples, not water solutions. However, the process still might be applicable in conjunction with another process such as distillation, where the components of the solution pass through a vapor phase (see Figure IV-66). The distilled water and organic vapors could be passed into a chamber and subjected to a continuous microwave discharge. The tests so far conducted have yielded virtually 100 percent degradation into simple gaseous products (H_2, CO, CO_2, CH_4, etc.).[132]

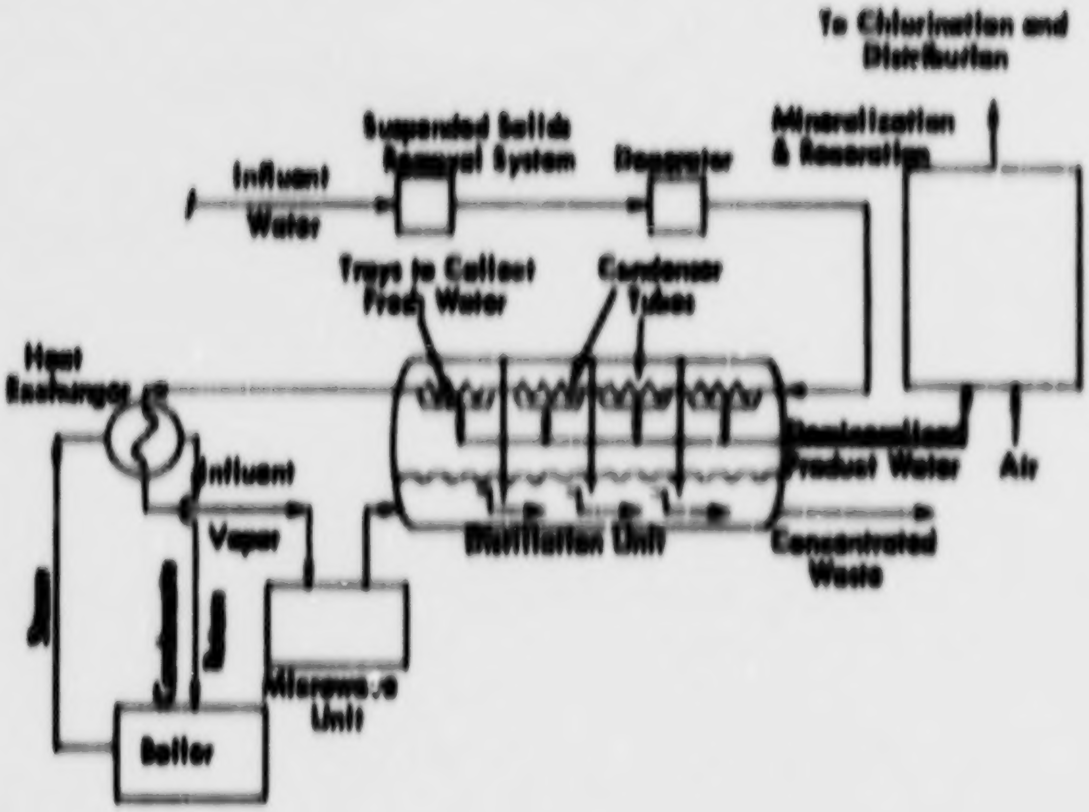
Radiochemical Cost.

No cost data are presented for radiochemical treatment. For the most part, the individual methods are still too much theory and not enough practice. None of the tests utilizing gamma and microwaves have progressed beyond laboratory scale. Ultraviolet has been tested on a pilot scale, but results are very inconsistent and contradictory. For information on the costs of the various types of radiation treatment, see References 130 and 140 for gamma radiation and 88 and 139 for ultraviolet. No cost data were located for microwave treatment.


Lead Shield
Water In
Treated Water Out
Cobalt 60
Clarification
Irradiator
Carbon Adsorption
Ion Exchange
To Chlorination and Distribution

Source: 159.

FIGURE IV-38
GAMMA RADIATION TREATMENT
DEVICE



To Chlorination and Distribution
Suspended Solids Removal System
Deaerator
Mineralization & Reaeration
Influent Water
Trays to Collect Fresh Water
Condenser Tubes
Heat Exchanger
Demineralized Product Water
Air
Influent
Vapor
Distillation Unit
Concentrated Waste
Microwave Unit
Boiler

Source: 80.

FIGURE IV-26
MULTISTAGE FLASH DISTILLATION
WITH MICROWAVE UNIT

Reverse Osmosis

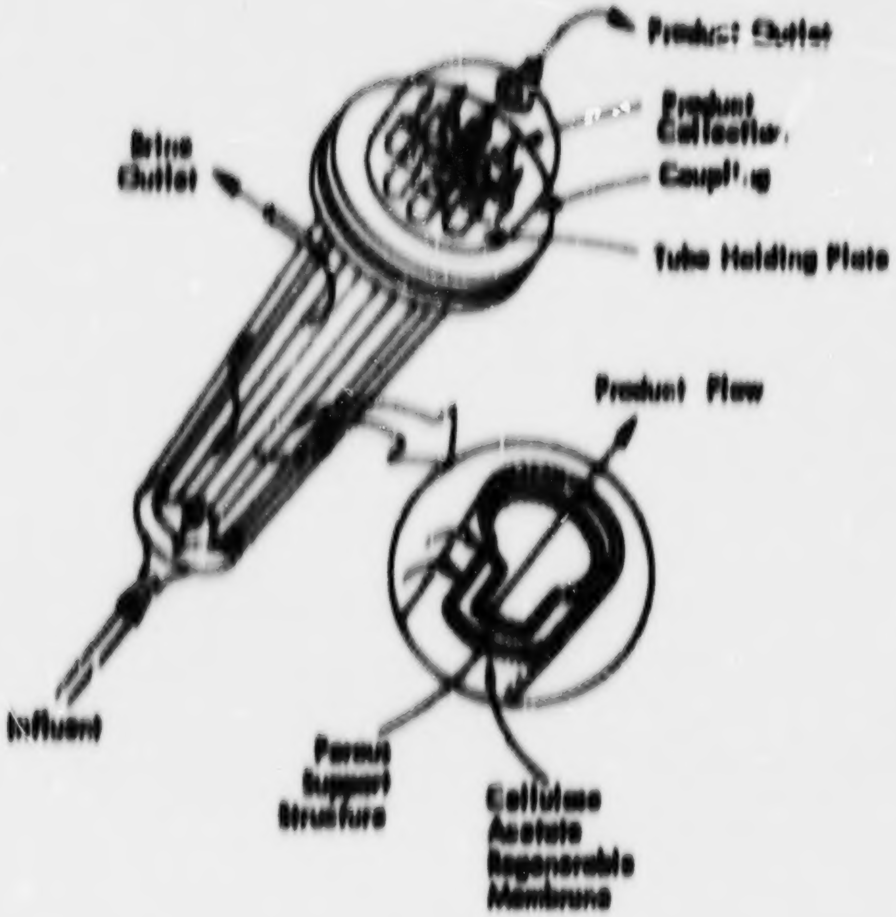
Process Description and Theory.

The reverse osmosis[137] process, a new development in the field of solute-solvent separation, consists of letting the fluid mixture of higher concentration flow under pressure through a membrane, and withdrawing desalinized product at atmospheric pressure and room temperature. The process has been applied to water purification and various other purposes involving the separation, concentration, or fractionation of substances in fluid solutions. Osmosis is the spontaneous flow of water from a less concentrated solution to a more concentrated solution through a semipermeable membrane. To obtain pure water in a similar process, the direction of water flow must be reversed (i.e., pure water must flow from a more to a less concentrated solution). This can be done by applying pressure on the more concentrated aqueous solution to reverse the flow of treated water. This is the "reverse osmosis" technique.

Reverse osmosis is similar to filtration, in the sense of removing liquid from a mixture by passing it through a device which retains the other components. However, there are two important differences. First, extra pressure has to be applied to the more concentrated solution to counteract the osmotic pressure from the opposite direction. Second, filters separate suspended matter primarily on the basis of size, whereas the semipermeability of the reverse osmosis membrane depends significantly on other factors as well. The basic principles underlying reverse osmosis are still controversial, and there is no generally accepted theory capable of explaining the mechanism.

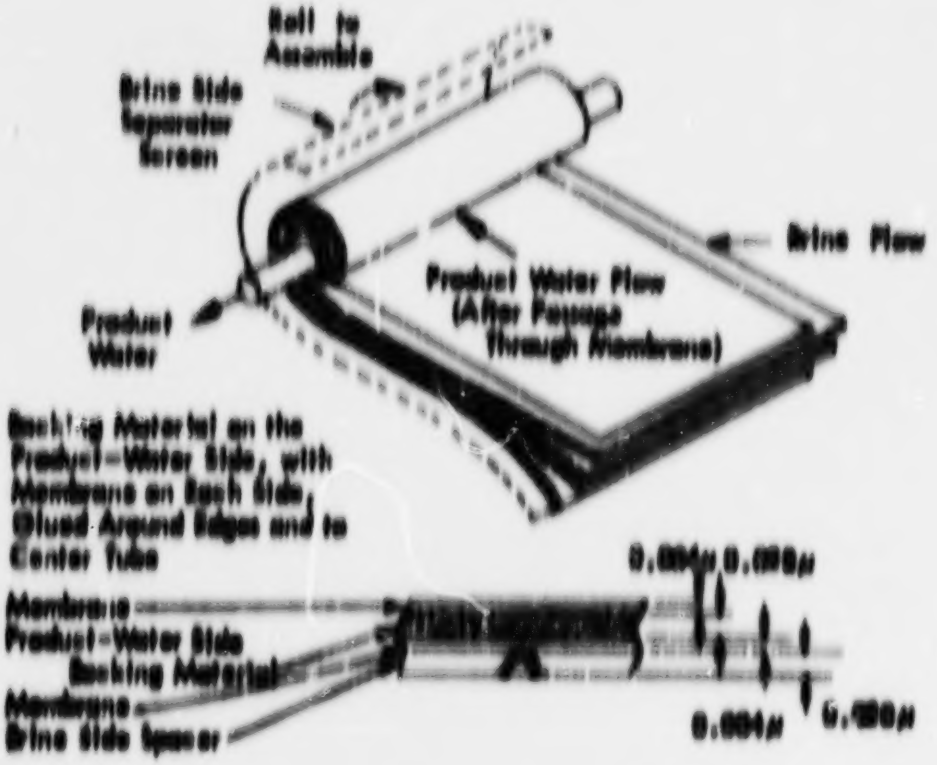
A typical reverse osmosis cell[78] consists of two detachable parts. One provides the inlet opening for the pressurized flow of feed solution. The other, the osmosis cell, provides the outlet opening for the withdrawal of the product solution after it has passed through the membrane. Cellulose acetate has been the most widely used membrane material. There are four modular designs for the osmosis cell--multiple plate, large tubes, spiral-wound, and hollow fine fiber. See Figures IV-87, IV-88, and IV-89 for examples of reverse osmosis apparatus.

Multiple plate devices have the membranes placed in a unit similar to a plate and frame filter press. The membranes in large tube units are rolled into cylindrical shape and inserted into porous fiberglass-reinforced epoxy tubes. The solution flows in the axial direction, while the product flows through the porous support. The membrane in a spiral-wound device is folded over a porous backing material and wrapped around a water take-off tube. This assembly is then placed inside a pressure vessel. In hollow fiber units, millions of hollow fibers (50 to 200μ in diameter) made of membrane material are packed into a special epoxy resin tube sheet. The input water, under high pressure, flows over the surface of the fibers, with the desalted water collecting inside the fibers and flowing out through the fibers' center pores.


Product Outlet
Product Collector
Brine Outlet
Coupling
Tube Holding Plate
Product Flow
Influent
Porous Support Structure
Cellulose Acetate Regenerable Membrane

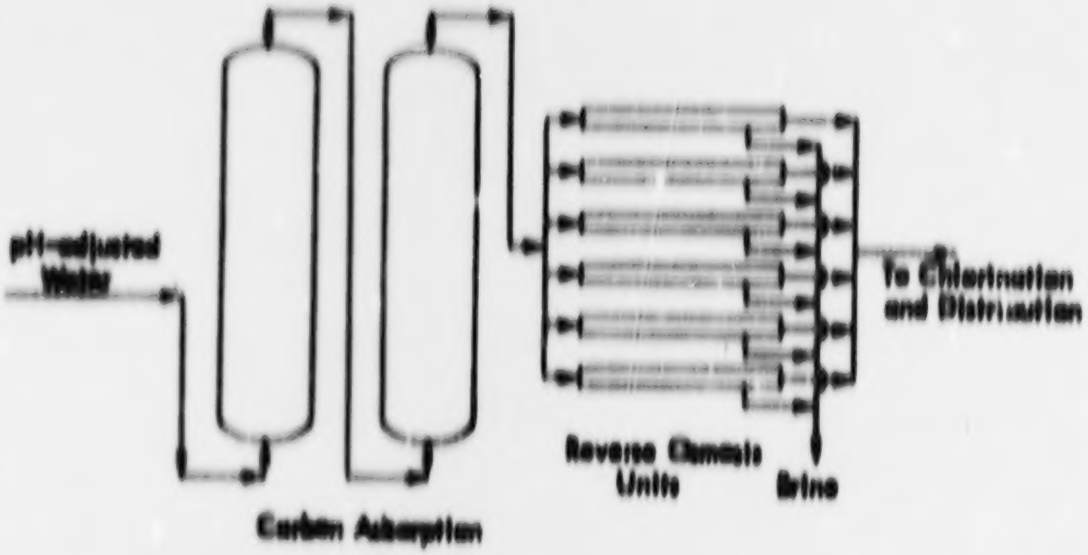
Source: 127.

FIGURE IV-57
REVERSE OSMOSIS
TUBULAR MODULE


Roll to Assemble
Brine Side Separator Screen
Brine Flow
Product Water Flow (After Passage Through Membrane)
Product Water
Backing Material on the Product-Water Side, with Membrane on Each Side, Glued Around Edges and to Center Tube
0.004μ 0.008μ
Membrane
Product-Water Side Backing Material
Membrane
Brine Side Spacer
0.004μ
0.030μ

Source: 107.

FIGURE IV-58
REVERSE OSMOSIS,
SPIRAL-WOUND MODULE


pH-adjusted
Water
Carbon Adsorption
Reverse Osmosis
Units
Brine
To Chlorination
and Distribution

Source: 198.

FIGURE IV-39
REVERSE OSMOSIS,
FLOW DIAGRAM

Reverse osmosis systems are now commercially available in a wide capacity range (from 9.5 liters/day to 567,750 liters/day).[115] Most existing commercial units are for treating brackish water (i.e., 1,000 to 5,000 mg/liter total dissolved salts). The flux through a particular membrane is determined by its thickness, chemical composition, and porosity. It also depends on system conditions such as temperature, differential pressure across the membrane, salt concentration of solution touching the membrane, and velocity of the feed moving across the membrane.

It is often necessary to treat the water being fed to a reverse osmosis plant to improve membrane efficiency and prevent scale formation. Turbidity is usually removed by sand filtration, sometimes with a coagulant added before the filter. Carbonate formation can be eliminated by adding acid to the feed. Post-treatment includes pH adjustment, degasification, disinfection, and others.

Cellulose acetate is the most frequently used membrane material because it possesses the strength and permeability necessary to be an effective osmotic membrane, is fairly stable, and is relatively inexpensive. Polyamide membranes are less pH sensitive, but tend to be more reactive to chemicals in the water, such as chlorine. Cellulose acetate membranes may undergo considerable hydrolysis at alkaline pH,necessitating adjustment to a lower pH before treatment. Dissolved organics in the water can interfere with reverse osmosis by fouling the membranes or even dissolving them if present in high enough concentrations. Consequently, oxidation or carbon adsorption treatment are necessary if organics are present. Activated carbon can be used to reduce chlorine residuals to a level harmless to the membranes.

__Application.__

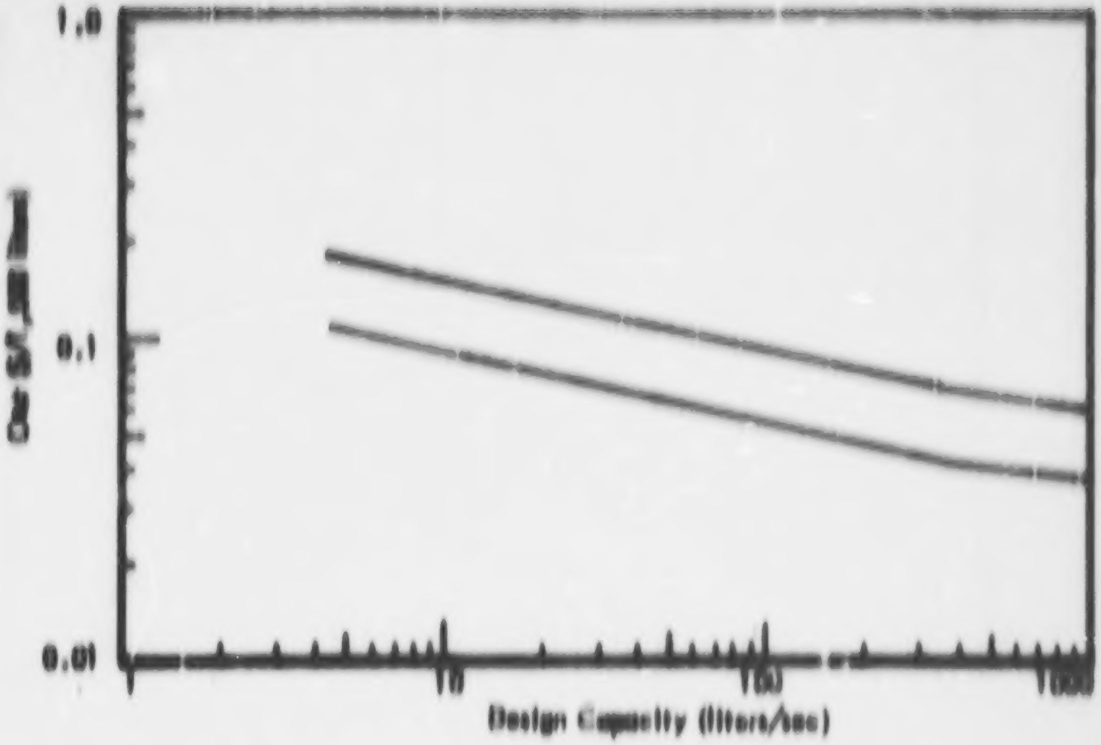
Considerable research has been conducted on the use of reverse osmosis for removing nickel from water. For example, Hauck investigated reverse osmosis for treating dilute nickel-plating solutions with nickel concentrations of up to 1,000 mg/liter. He used Batch 316-type cellulose acetate membranes operated at a pH of 4 to 6, a temperature of 24 C, a flow of 1,469 liters per square meter per day,and a pressure of 21 kgf/cm^2. His average removal efficiency was 91.3 percent.[116] Efficiencies up to 99.9 percent can be achieved if ultra-thin membranes of cellulose acetate, cellulose methyl sulfonate, or cellulose n-propyl sulfonic acid are used at a production rate of 0.12 liter/m^2 of membrane per day.[131]

Chlorinated hydrocarbon insecticides can also be removed by reverse osmosis under certain conditions. Although some insecticides (such as DDT and Aldrin) interact with the membrane, proper control of pH and flow rate is usually sufficient to prevent membrane deterioration.[109] Hindin[130] studied removal efficiencies of cellulose acetate membranes for several insecticides. Lindane was reduced from 50 to 8 ng/liter at 0.073 liter/cm^2 per day; DDT was reduced from 910 to less than 3 ng/liter at 0.081 liter/cm^2 per day; TDE (DDD) was reduced from 23 to less than 0.006 ng/liter at 0.061 liter/cm^2 per day; and BHC was reduced from 638 μg/liter to 306 ng/liter at 0.057 liter/cm^2 per day.

Costs for Reverse Osmosis.

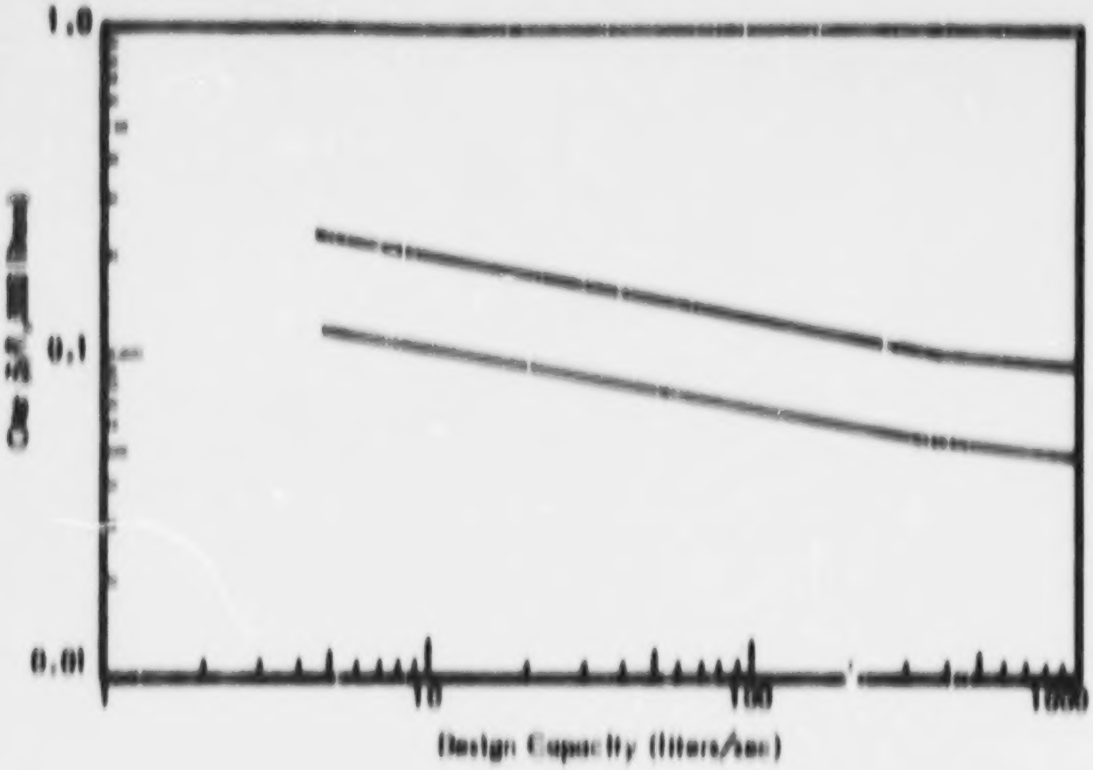
Reverse osmosis costs were estimated over a range of flows similar to those of other processes. The section on ultrafiltration does not give cost data, but the costs should be quite close to those for reverse osmosis since the processes are quite similar.

The capital cost (Figure IV-60) for reverse osmosis was amortized at 7 percent over twenty years, and included engineering and design costs. Operating and maintenance costs (Figure VI-61) included power and membrane replacement. Brine disposal was not included. A raw water salt content of 800 mg/liter treated to 50 mg/liter was assumed. Total cost is shown in Figure IV-62. A wide band is shown in the curves to show disparities between sources. The lower line shows estimated costs, and the upper line the highest costs given in the various sources. Figure IV-63 shows land requirements as a function of design capacity for reverse osmosis plants.



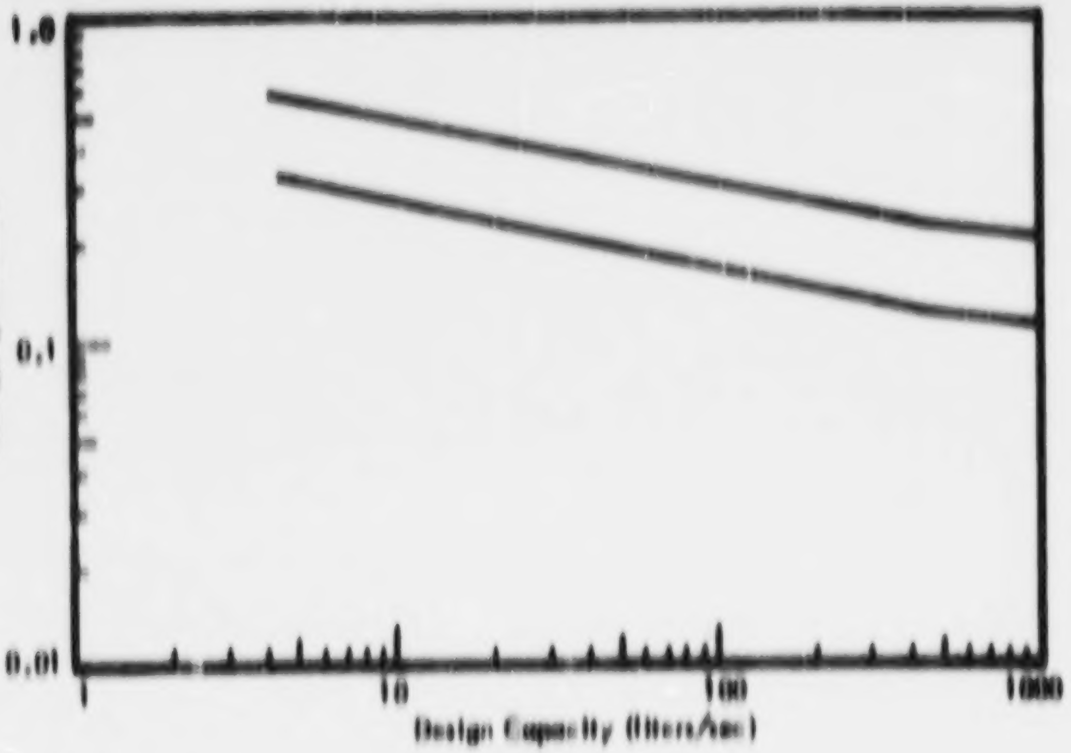
Source: See Figure A-84.

FIGURE IV-60
REVERSE OSMOSIS:
CAPITAL COST RANGE
1974



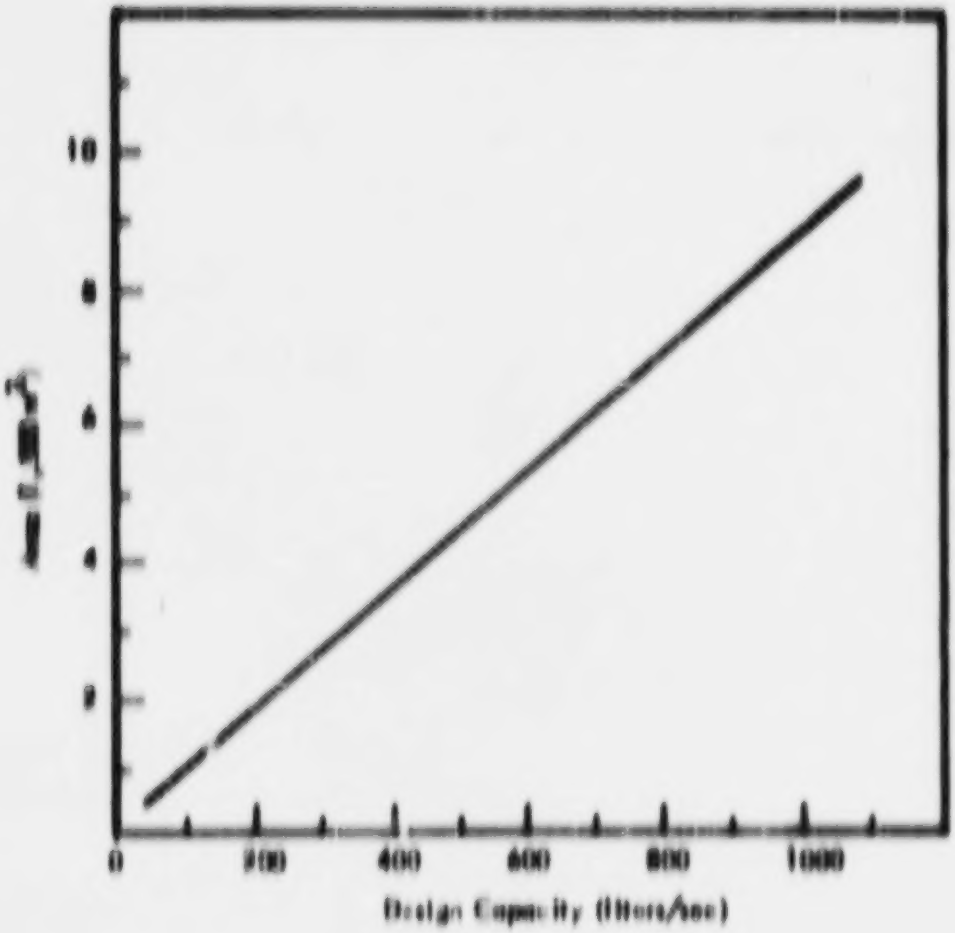
Source: See Figure A-35.

FIGURE IV-41
REVERSE OSMOSIS: OPERATION AND
MAINTENANCE COST RANGE
1974



Source: See Figure A-36.

FIGURE IV-62
REVERSE OSMOSIS:
TOTAL COST RANGE
1974



Source: 198.

FIGURE IV-63
REVERSE OSMOSIS:
LAND REQUIREMENTS

Ultrafiltration

Process Description and Theory.

Membrane filtration involves surface filtration at relatively high pressures and low flowrates through dynamically formed membranes.[64] Ultrafiltration membranes (organic polymer films 0.125 to 0.25 mm thick) are two-layered, containing a thin (0.1 to 10 μ) separation layer on a relatively porous supporting substructure. The separation layer contains pores ranging in size from 5 to 100 Å. The separation layer in ultrafiltration devices is adjacent to a pressurized chamber containing the influent. Under the influence of pressure, small molecules will pass through the membrane with the larger molecules retained in the pressurized chamber. Pressure drop across the membrane ranges from 141 to 2812 g/cm². Typical hydraulic loadings range from 50.8 to 693 liters/m².

Ultrafiltration units usually consist of plate configurations having channel dimensions of about 0.25 mm or tubular configurations having inside diameters of 5 to 25 mm. The plate device is made up of sheets of porous material upon which the separation membrane has been cast. The sheets are arranged in a parallel fashion and terminate in a collection manifold. The feed solution passes between the plates and the effluent permeates the membrane and passes up the porous support to the exit header.

Tubular devices (see Figure IV-64) consist of a support tube (made of sintered porous polymeric material or fabricated as a composite of fiberglass and polyester or epoxy materials) with the membrane placed inside the tube. The feed flows through the tube and the effluent permeates the membrane, due to the operating pressure. The effluent passes into the porous supporting material and is collected in a manifold.

Backwashing is unnecessary since the separation membrane's pores do not clog. Also, there is no tendency for solids to build up on the membrane. If throughputs are too low, concentration gradients can be established, although these decrease the unit's efficiency. Since membrane treatment methods are generally used as effluent polishing techniques, it is assumed that the influent will already have been subjected to routine conventional treatment methods. As an effluent polishing technique, ultrafiltration is used to remove those contaminants not removed by other treatment methods. These include fine particulates and colloids, refractory organics, high molecular weight bio-polymers, soluble emulsified oils, bacteria, and viruses.

Application.

No data were located regarding the use of ultrafiltration for any of the twelve subject contaminants, but the method would be applicable to certain states of some of the contaminants. For instance, ultrafiltration could be used to remove any subject contaminant occurring in fine particulate or colloidal form. This would generally apply to the metal contaminants and the water-insoluble insecticides. The higher weight insoluble liquid organics, such as the PCB's, could be removed in a fashion similar to emulsified oils.[170] The process would also be useful in removing insecticide-oil emulsions, such as might occur near agricultural areas. Generally speaking, solids and organic removals are better than 95 percent, with effluent concentrations of only a few mg/liter.[99]

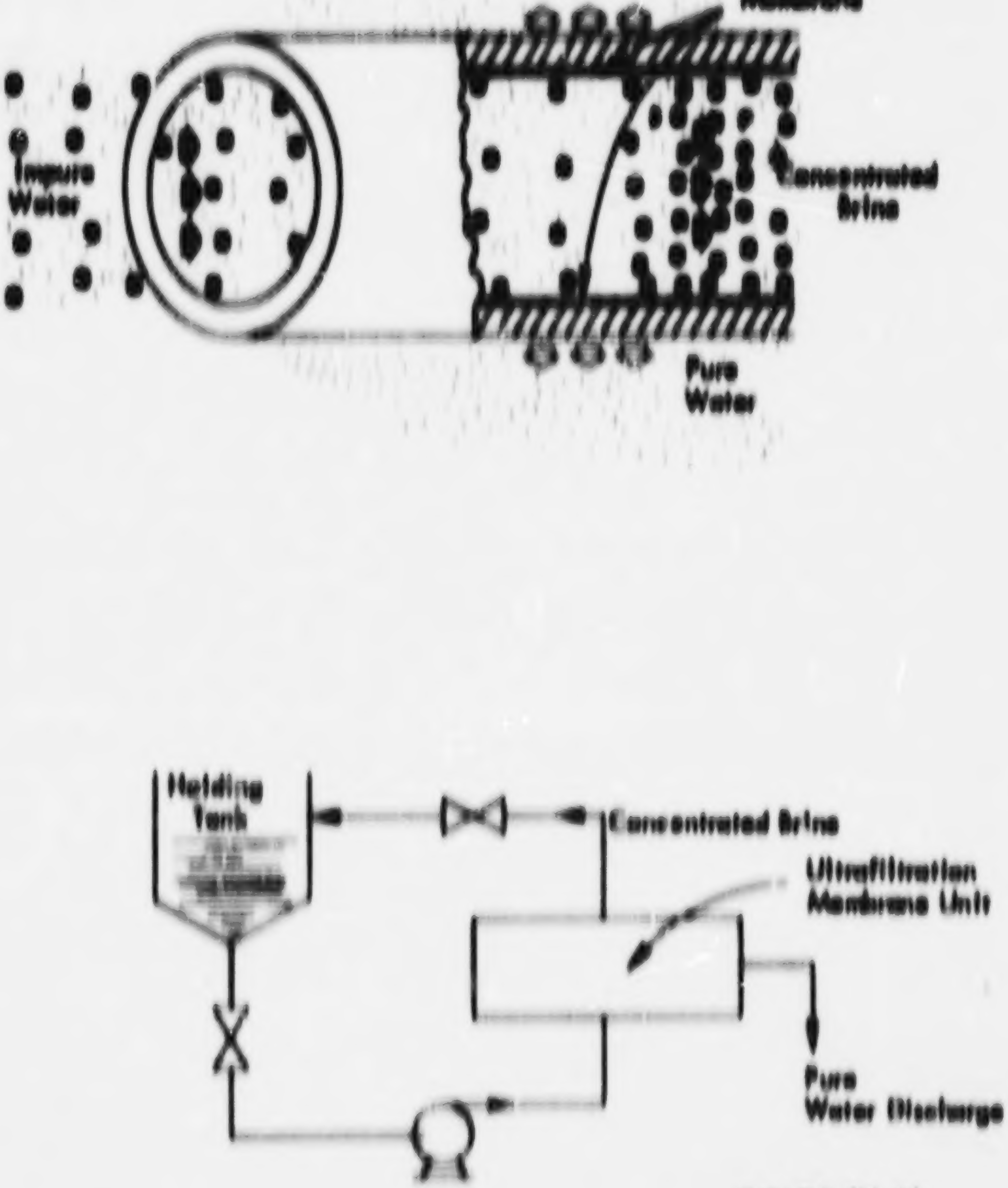

Membrane
Impure Water
Concentrated Brine
Pure Water
Holding Tank
Concentrated Brine
Ultrafiltration Membrane Unit
Pure Water Discharge

FIGURE IV-44
TUBULAR ULTRAFILTRATION
DEVICE

Source: 180.

SECTION V

BIBLIOGRAPHY

The references in this bibliography are the result of an extensive six-month literature search. This list is by no means exhaustive, but consists of those references cited or otherwise directly used in writing this report. The literature search involved a review of the relevant literature published since 1966. Over fifty major technical and scientific journals were searched. Water Resources Abstracts, Excerpta Medica, Engineering Index, Pollution Abstracts, Chemical Abstracts, Applied Science and Technology Index, Science Abstracts, and Environmental Abstracts were searched for other relevant articles. The University of Wisconsin Water Resources Information Center computer file was searched using appropriate "key words". Over fifty books and government reports were also read for this report. Manufacturers literature was utilized for process descriptions and cost information.

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SECTION VI
GLOSSARY

Acid. 1) Any compound which can react with a base to form a salt, the hydrogen of the acid being replaced by the metallic or positive ion.
2) A substance that dissolves in water with the formation of a hydrogen ion (H^+).

Activated Carbon. Carbon particles usually obtained by carbonization of cellulosic material in the absence of air and possessing a high adsorptive capacity.

Adsorption. The phenomenon by which a gas, liquid, or solid adheres to the surface of a body.

Aeration. The process of mixing air and water by such methods as the spraying of liquid in the air, bubbling air through the liquid, agitating the liquid to promote surface absorption of air, or trickling the liquid through a column of packed media or trays.

Aeration Tank. A tank in which sludge, wastewater, or other liquid is aerated.

Aldrin. A chlorinated hydrocarbon insecticide; specifically 1,2,3,4,10,10 - hexachloro-1,4,4a,5,8,8a - hexahydro - 1,4,5,8 - dimethanonaphthalene.

Alkalinity. The capacity of a solution to neutralize an acid.

Alum. A hydrated aluminum sulfate $Al_2(SO_4)_3 \cdot 14\ H_2O$ or potassium aluminum or ammonium aluminum sulfate. Alum can be used to coagulate colloidal pollutants for better settleability.

Anion. Ion with a negative charge. It can be removed at the anode of an electrolytic cell.

Anode. 1) the positive terminal of an electrolytic cell. 2) The electrode at which oxidation occurs in an electrolytic cell. 3) The negative terminal of a source that is delivering current.

Aromatic Hydrocarbons. Unsaturated hydrocarbons, such as benzene (C_6H_6) or naphthalene ($C_{10}H_{14}$), having a ring or fused ring structure with the general formula C_nH_{2n-6}.

Backwashing. The process of cleaning a filter by reversing the flow of water through it.

Base. 1) A substance that dissolves in water with the formation of hydroxyl ions (OH^-).
2) A compound which can react with an acid to form a salt, the hydroxyl ion of the base being replaced by the acid anion.

Biosorption. The adsorption of matter on the surface of biological slimes.

Bis-ether. An organic compound formed of two identical organic radicals joined by an oxygen atom; chemically R-O-R.

Brackish. Water having a mineral content in the general range between fresh water and seawater. Water containing from 1,000 to 10,000 mg/liter of dissolved solids.

Breakpoint Chlorination. Addition of chlorine to water or wastewater to the point where the chlorine demand has been satisfied and further additions result in a free residual that is directly proportional to the amount added beyond the breakpoint.

Carbohydrate. A compound of carbon, hydrogen and oxygen, usually having hydrogen and oxygen in a proportion of two to one.

Carcinogen. A substance having the potential for producing cancers or increasing the cancer-causing potential of other substances.

Catalyst. A substance that alters the rate at which a chemical reaction takes place but which itself remains unchanged.

Cathode. 1) The negative terminal of an electrolytic cell. 2) The electrode at which reduction occurs in an electrolytic cell. 3) The positive terminal of a source that is delivering current.

Cation. Ion with a positive charge. It can be recovered at the cathode of an electrolytic cell.

Chelate. An organic compound which binds with a metal at two or more points.

Chlordane. A chlorinated hydrocarbon insecticide, specifically 1,2,4,5,6,7,8,8-octachloro - 2,3,3a,4,7,7a - hexahydro - 4,7 - methanoindene.

Chlorination. The application of chlorine to water or wastewater, generally for the purpose of disinfection, but frequently for oxidation purposes or taste and odor control.

Chronic Toxicity. Long term toxicity.

Clarification. Any process which reduces the concentration of suspended matter in a liquid.

Clarifier. A unit designed to achieve clarification; usually applied to sedimentation tanks or basins.

Clay. Soil consisting of inorganic material with grain size smaller than 0.002 mm.

Coagulation. In water and wastewater treatment, the destabilization and initial aggregation of colloidal and finely divided matter by the addition of floc-forming chemicals, such as lime, alum, or polyelectrolytes.

Colloid. A finely divided dispersion of a material (0.01-10 micron-sized particles), called the "dispersed phase" (solid), in another material, called the "dispersed medium" (liquid). Normally the particles are negatively charged.

Contamination. A general term signifying the introduction into a material or media of such substances as microorganisms, chemicals, wastes or sewage which render the material less desirable for its intended use.

Covalent Bond. Nonionic chemical bond formed by shared electrons.

DDD. A chlorinated hydrocarbon insecticide specifically 1,1- dichloro - 2,2 - bis (p-chlorophenyl) ethane.

DDT. A chlorinated hydrocarbon insecticide specifically 1,1,1 - trichloro - 2,2 - bis (p-chlorophenyl) ethane.

Desorption. A phenomenon where an adsorbed molecule leaves the surface of the adsorbent.

Dieldrin. A chlorinated hydrocarbon insecticide, specifically 1,2,3,4,10,10 - hexachloro - 6,7 - epoxy - 1,4,4a,5,6,7,8,8a - octahydro - 1,4,5,8 - endo-exo-dimethanonaphthalene.

Distillation. Vaporization of a liquid followed by condensation of the vapor.

Effluent. The liquid which leaves a unit operation or treatment process.

Electrodialysis. A membrane separation process utilizing a voltage impressed across cation-anion selective membrane pairs to remove dissolved solids from aqueous solutions.

Emulsion. A heterogeneous system consisting of at least one immiscible liquid dispersed in another in the form of microscopically visible droplets.

Endrin. A chlorinated hydrocarbon insecticide, specifically the endo-endo isomer of Dieldrin.

Feeder, Chemical. A mechanical device for applying chemicals to water or wastewater, often at a rate controlled by the rate of flow.

Filter. A device for screening solids from liquids based on molecule or particle size.

Flowmeter. An instrument for measuring the rate of flow of a fluid moving through a pipe or duct system.

Gamma Ray. High energy electromagnetic radiation of wavelengths between 0.005 and 1.40 Å with great penetrating power, emitted as a result of radioactive decay or shifts of orbital electrons.

Halide. Any binary compound of a halogen.

Halogen. Any one of the chemically related elements fluorine, chlorine, bromine, iodine, and astatine.

Hard Water. Any water that contains an excess of metallic cations in solution that react with soap to form a precipitate.

Heptachlor. A chlorinated hydrocarbon insecticide, specifically 1,4,5,6,7,8,8 - heptachloro - 3a,4,7,7a - tetrahydro - 4,7 - methanindene.

Hydrocarbon. A compound containing only carbon and hydrogen.

Hydrolysis. The chemical decomposition of a substance by water, in which the water itself is also decomposed.

Hydrophilic. A term applied to substances with high affinity for water.

Hydrophobic. A term applied to substances with low affinity for water.

Influent. Fluid inflow.

Ion. An atom or molecule possessing an electrical charge.

Ion Exchange. A reversible interchange of ions between a liquid and a solid involving no radical change in the structure of the solid. The solid can be a natural zeolite or a synthetic resin.

Ionic Strength. A term reflecting the extent of the interaction of ions with one another in a solution.

Ionization. The conversion of neutral particles into ions.

Ionization Constant. A value relating the equilibrium concentrations of the dissociated and undissociated forms of an ionizable compound in solution at a given temperature.

Isomers. Those molecules which have the same number and kind of atoms but different molecular configurations.

Isotopes. Elements with the same atomic number having different numbers of neutrons in the nucleus.

LD_{50}. Fifty percent lethal dose, the dosage at which 50 percent of the test population dies.

Lindane. A chlorinated hydrocarbon insecticide specifically 1,2,3,4,5,6 - Hexachlorocyclohexane.

Malathion. An organo-phosphorus insecticide, specifically S-(1,2 - dicarbethoxyethyl) - O,O -dimethyldithiophosphate.

Methoxychlor. A chlorinated hydrocarbon insecticide, specifically, 1,1,1 - Trichloro-2,2 - bis (p-methoxyphenyl) methane.

Microwaves. Electromagnetic radiation with wavelengths between 1 and 100 cm.

Neutralization. The reaction of an acid and a base to achieve a solution that is neither acidic nor basic.

Nonelectrolyte. A material, the aqueous solution of which is not conductive to an electric current.

Osmosis. The diffusion of a solvent through a semi-permeable membrane into a more concentrated solution.

Ozone. Triatomic molecular oxygen, O_3.

Parathion. An organophosphorus insecticide specifically O,O - diethyl O-p-nitrophenyl thiophosphate.

pH. The negative logarithim of the hydrogen ion concentration.

Polymeric Materials. Organic material in the form of long chains of repeating small organic molecules (monomers).

Potable Water. Water sufficiently pure for human consumption.

Raw Water. Untreated water.

Reservoir. A pond, lake, tank, basin or other space used for the storage, regulation, and control of water.

Residual Chlorine. The amount of chlorine left in the treated water that is available to oxidize contaminants if they enter the stream.

Reverse Osmosis. The process in which a solution is pressurized to a degree greater than the osmotic pressure of the solvent, causing it to pass through a membrane in a direction opposite that of conventional osmosis.

Salt. A compound made up of the positive ion of a base and the negative ion of an acid.

Saturated Hydrocarbon. An organic compound having the formula C_nH_{2n+2}.

Scaling. A salt formation on boundary surfaces due to super saturation.

Sedimentation. The settling of suspended matter from a liquid usually aided by provision of decreased velocities and increased retention times.

Sludge. The solid residues left following a treatment process.

Softening. The process of removing metallic cations from water.

Solvation. The chemical and physical processes involved in the solution of soluble substances.

TL_m: Median tolerance limit; the concentration at which 50 percent of the test organisms can survive for a specified period of exposure.

TLV. Threshold limit value; the concentration below which no adverse health effects are observed.

Toxaphene. A mixture of polychlorobicyclic terpenes; used as a chlorinated hydrocarbon insecticide.

Toxic Substance. Any substance causing adverse effects to an organism when ingested, inhaled or otherwise brought into contact.

Ultrafilters. Filters with membrane elements containing pores of 5 to 100 Å.

Ultraviolet Radiation. Electromagnetic radiation of wavelengths less than 4,000 Å, just shorter than visible light.

Underflow. The bottom discharges from a clarifier or thickener.

Zeolite. Various natural or synthetic silicate minerals used as ion exchangers or adsorbents.

APPENDIX

This appendix presents the sources for all the information used to formulate the treatment method cost curves. Each point on the curves was derived from the numbered reference listed below the curve. The numbers refer to the numbered bibliography entries. Those points marked "estimated" were based on previous company studies or information supplied by the manufacturers. All information was updated to 1974. These curves are presented in English units as all of the data were in English units and the initial curves were plotted in English units.

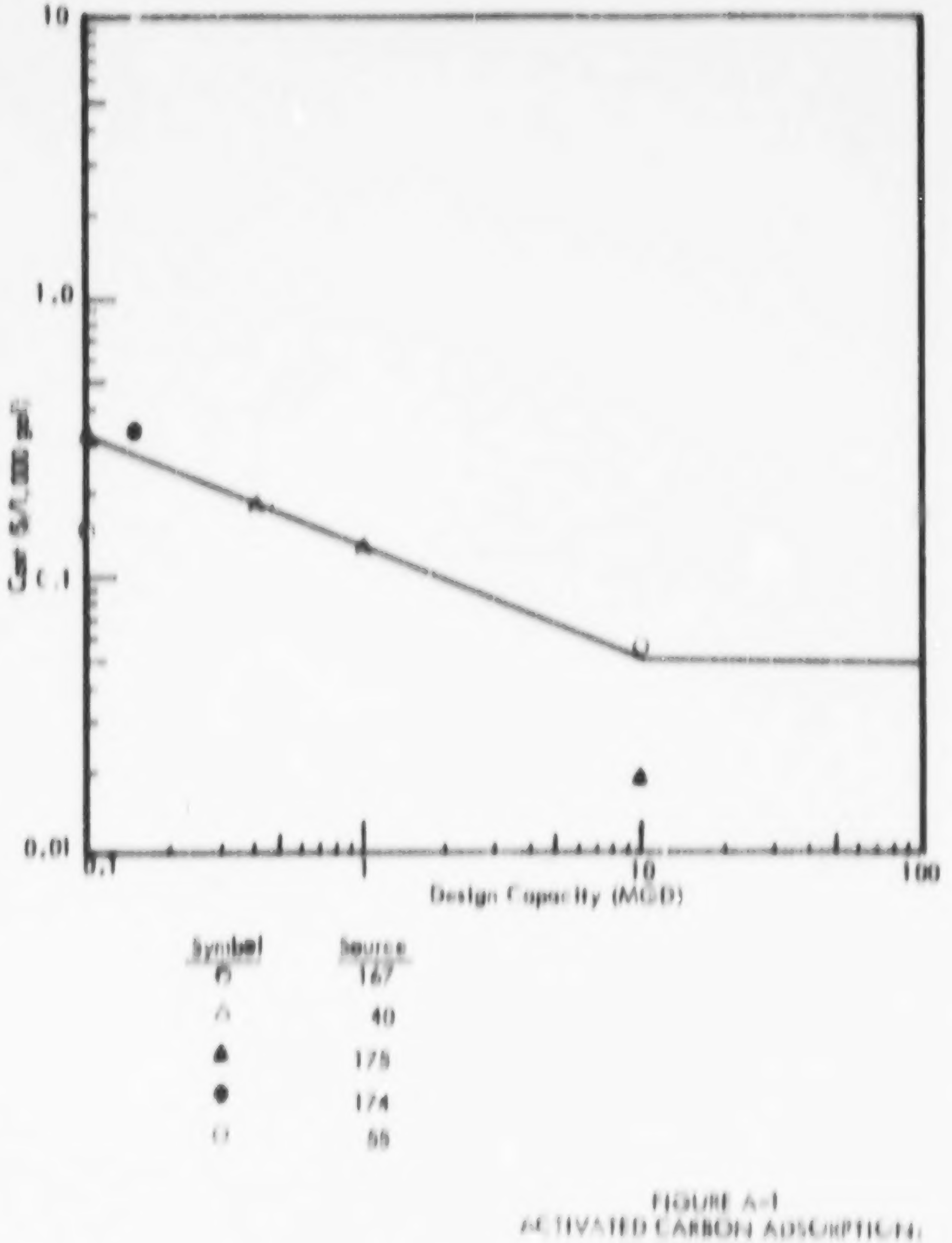


FIGURE A-1
ACTIVATED CARBON ADSORPTION:
CAPITAL COST
1974

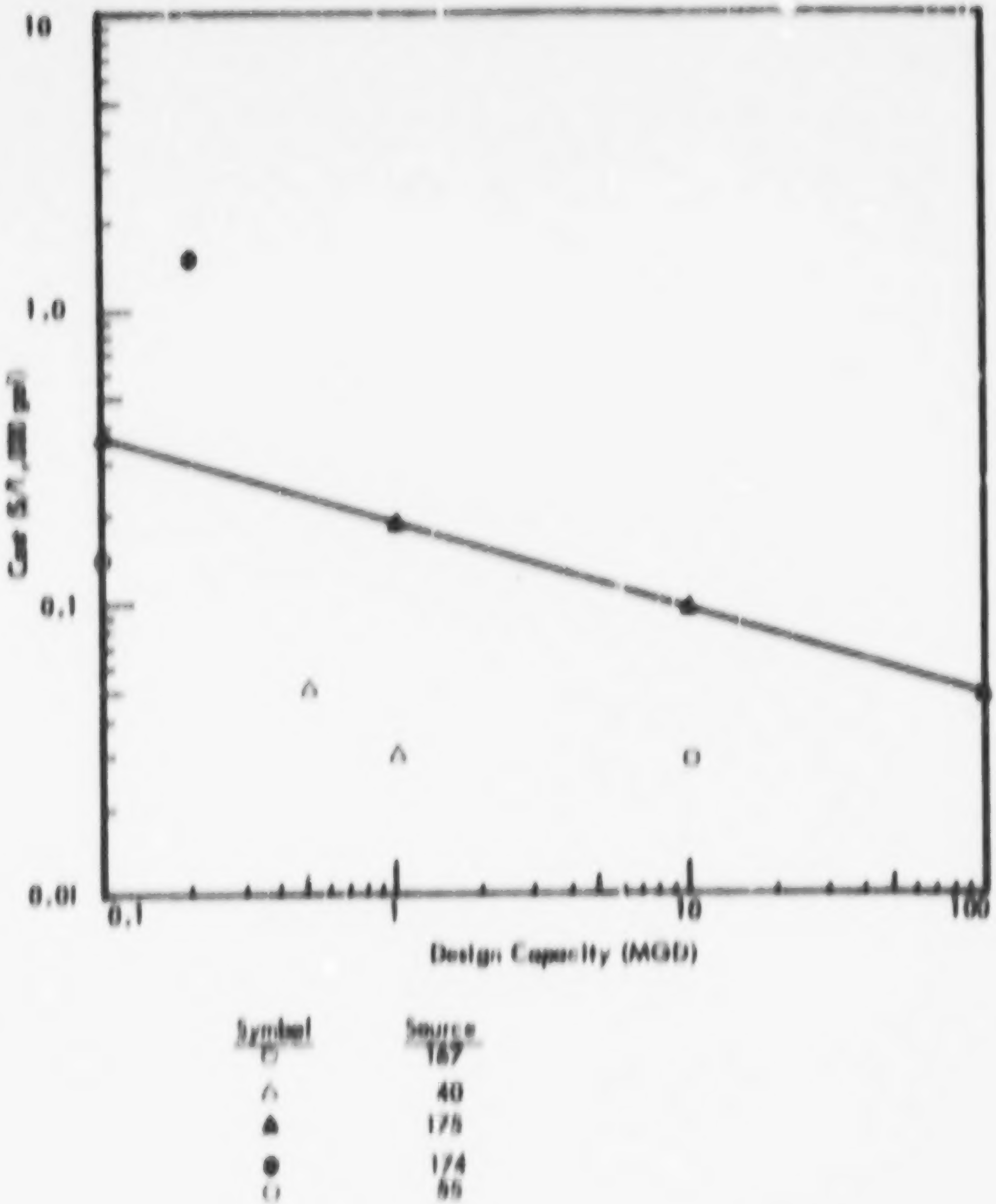


FIGURE A-7
ACTIVATED CARBON ADSORPTION:
OPERATION AND MAINTENANCE COSTS
1974

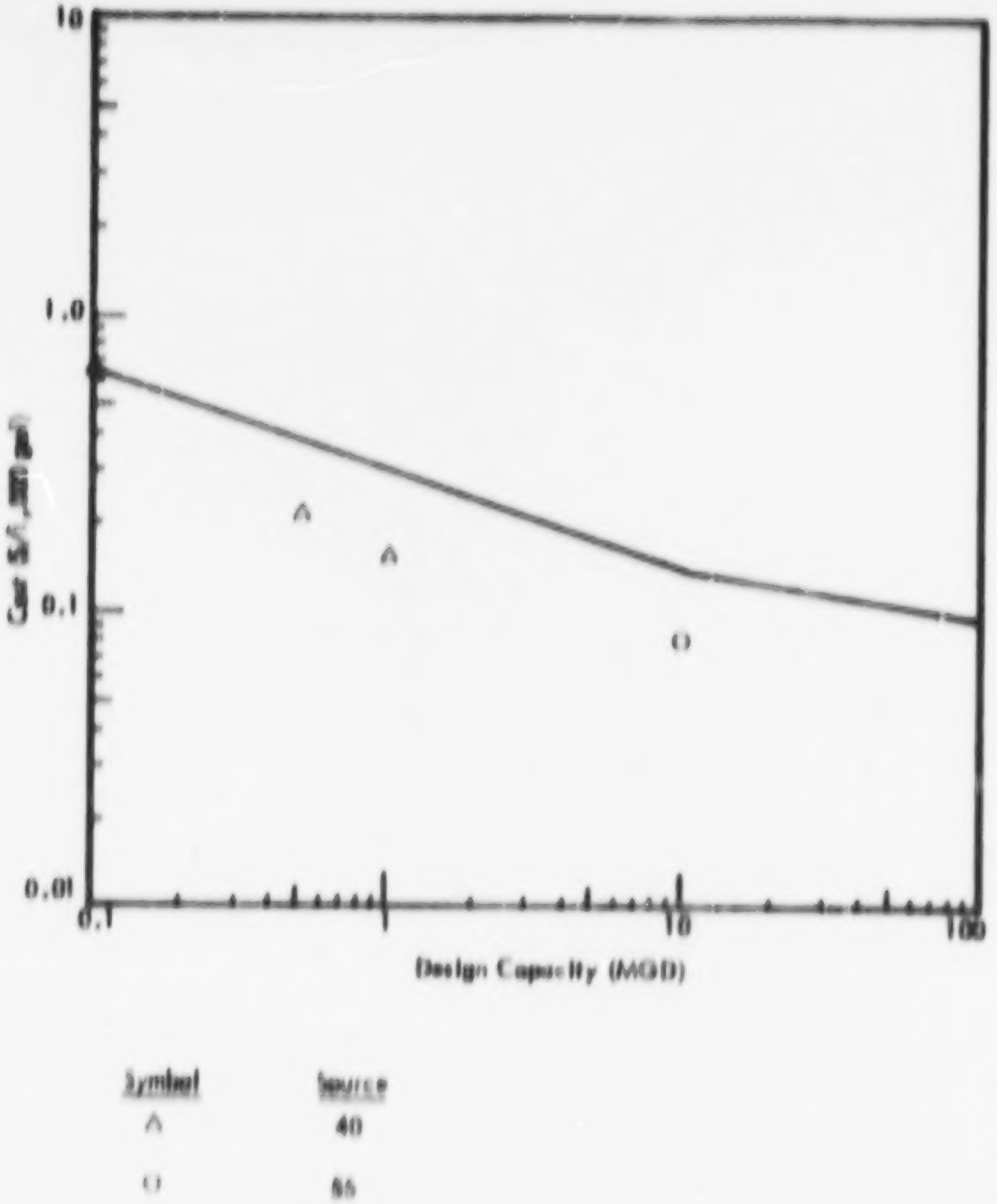


FIGURE A-3
ACTIVATED CARBON ADSORPTION,
TOTAL COST
1974

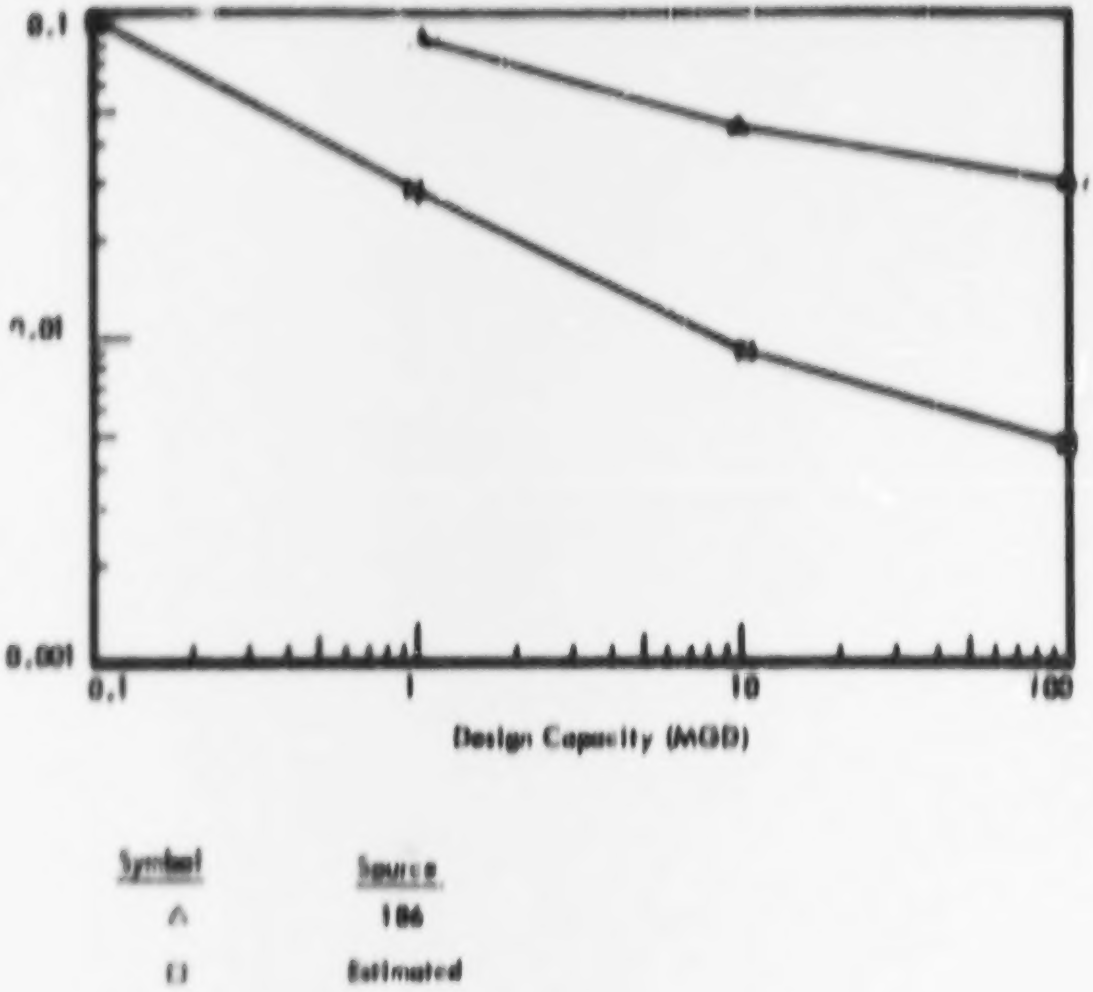
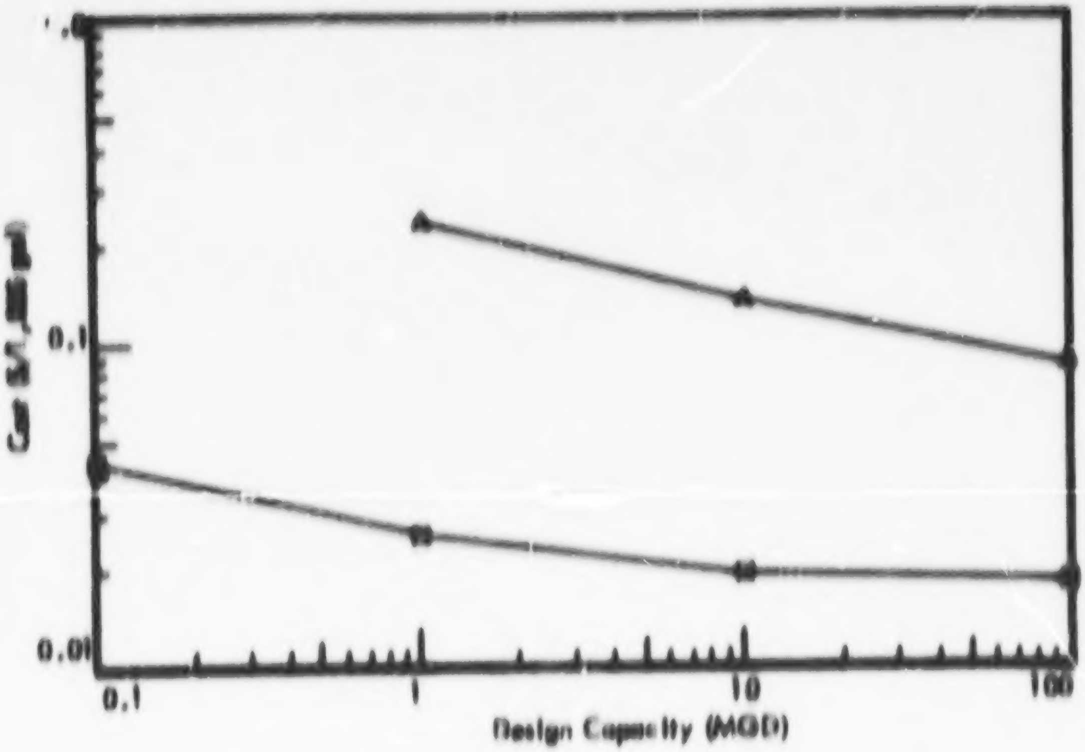


FIGURE A-4
OZONATION:
CAPITAL COST RANGE
1974



Symbol	Source
△	186
○	Estimated

FIGURE A-5
OZONATION,
OPERATION AND MAINTENANCE
COST RANGE
1974

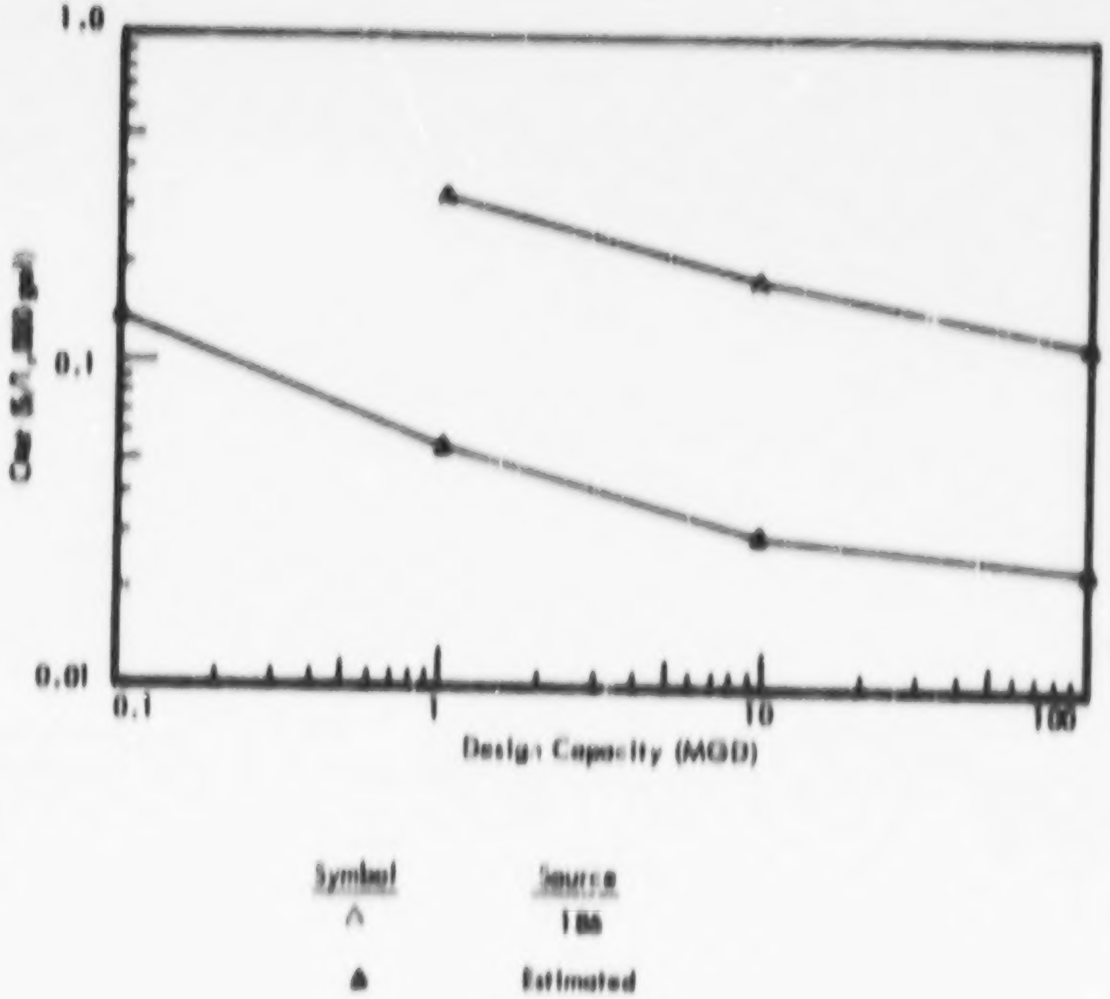
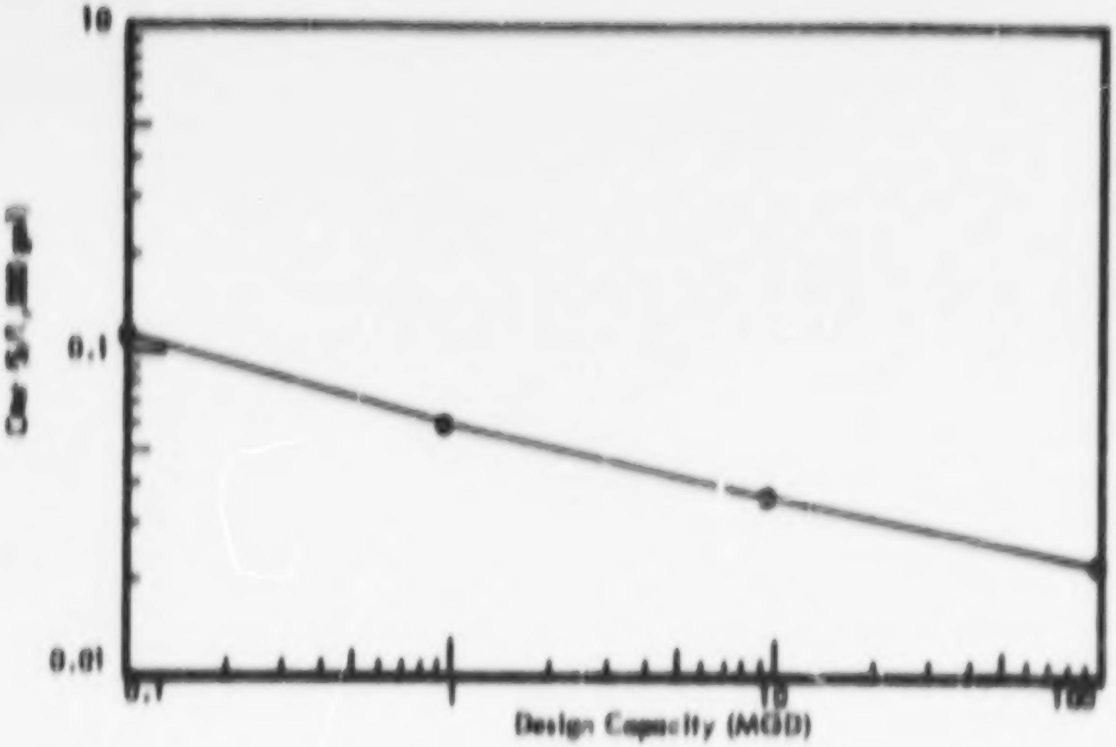


FIGURE A-6
OZONATION:
TOTAL COST RANGE
1974



Symbol	Source
●	Estimated

FIGURE A-7
LIME COAGULATION, SEDIMENTATION,
AND FILTRATION: CAPITAL COST
1974

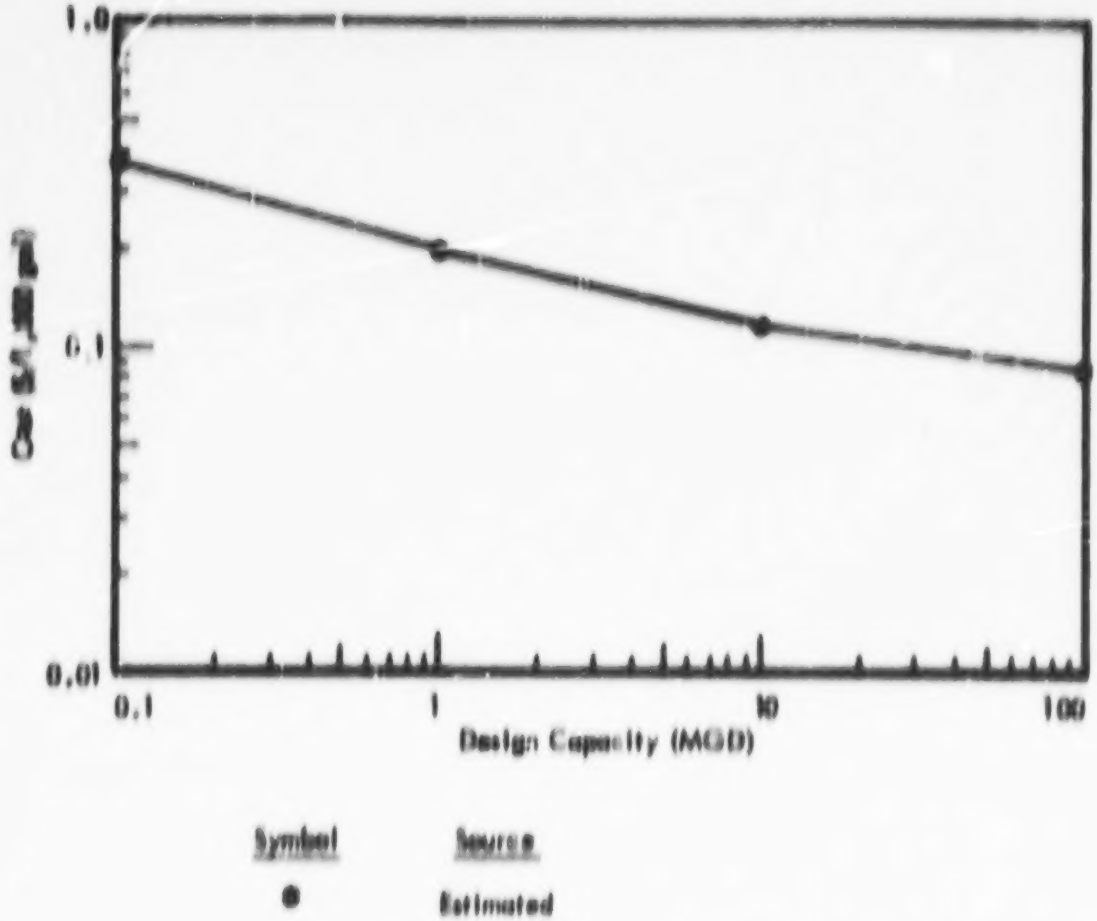


FIGURE A-8
LIME COAGULATION, SEDIMENTATION, AND FILTRATION:
OPERATION AND MAINTENANCE COSTS
1974

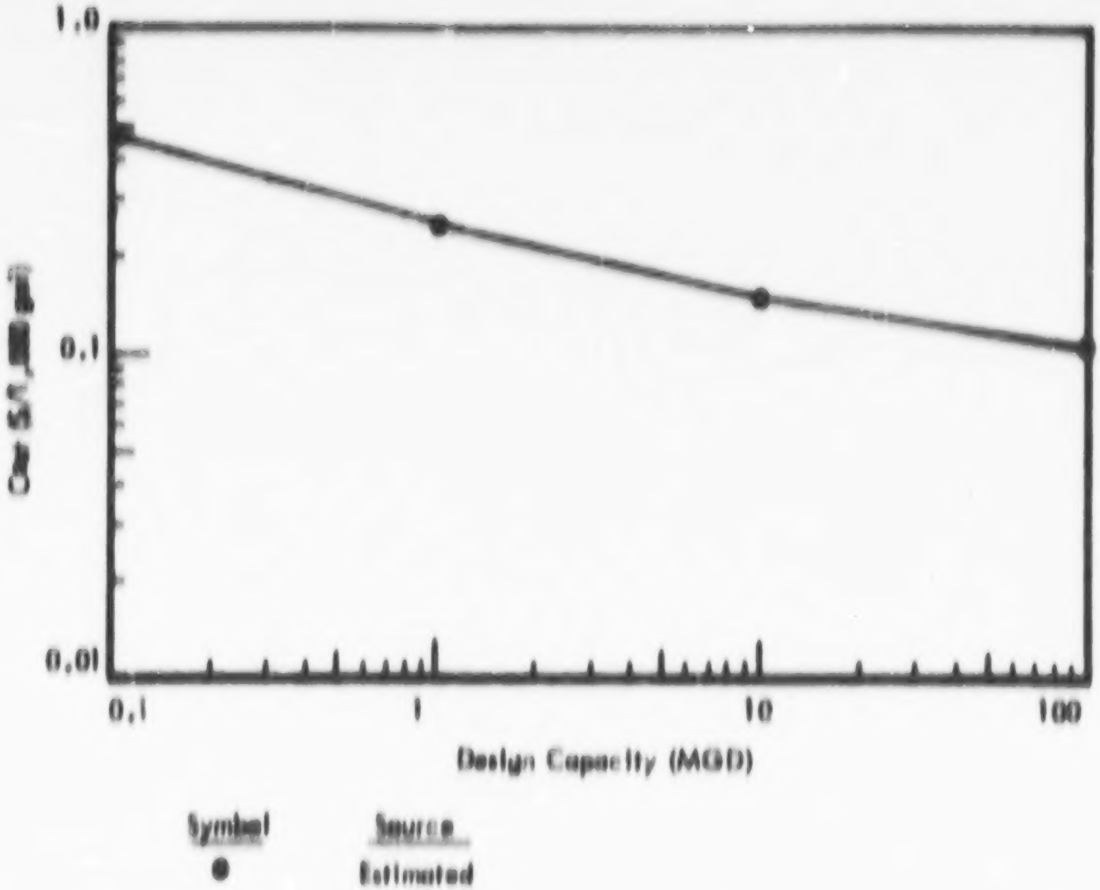


FIGURE A-9
LIME COAGULATION, SEDIMENTATION,
AND FILTRATION: TOTAL COST
1974

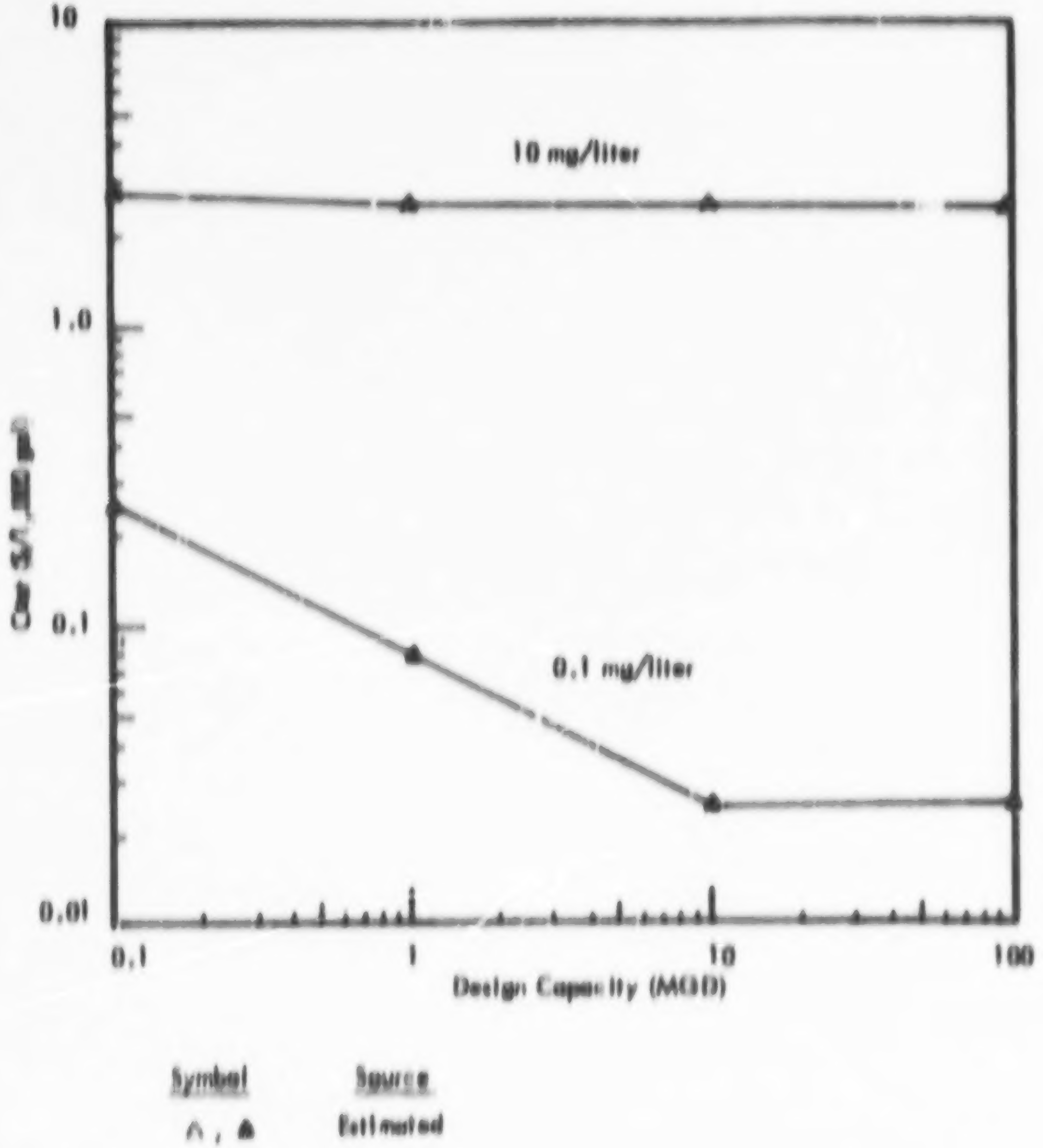


FIGURE A-10
CHITOSAN COAGULATION
COBALT, NICKEL, MOLYBDENUM, TUNGSTEN, VANADIUM
OPERATION AND MAINTENANCE COST RANGE
1974

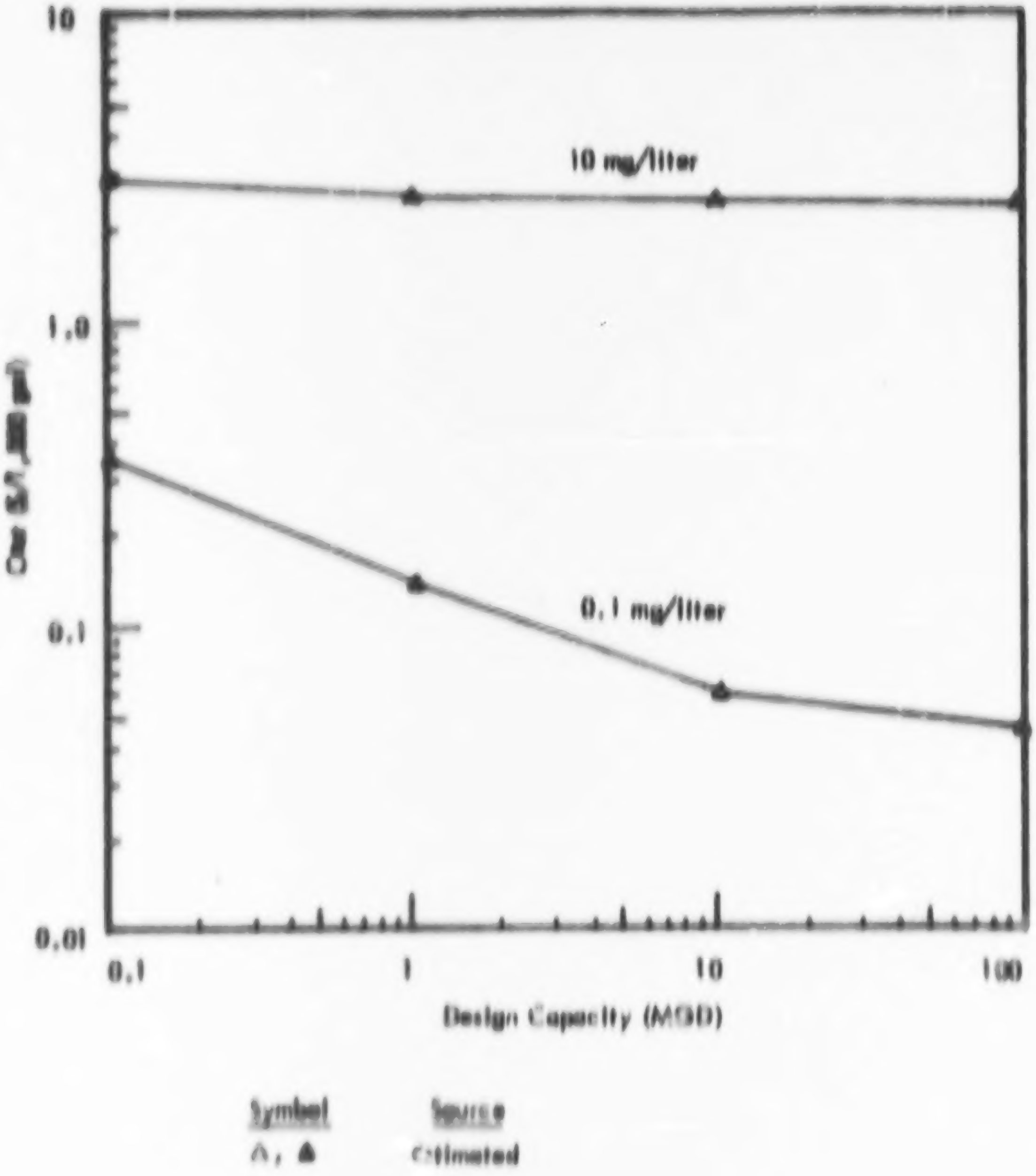


FIGURE A-11
CHITOSAN COAGULATION
COBALT, NICKEL, MOLYBDENUM, TUNGSTEN, VANADIUM:
TOTAL COST RANGE
1974

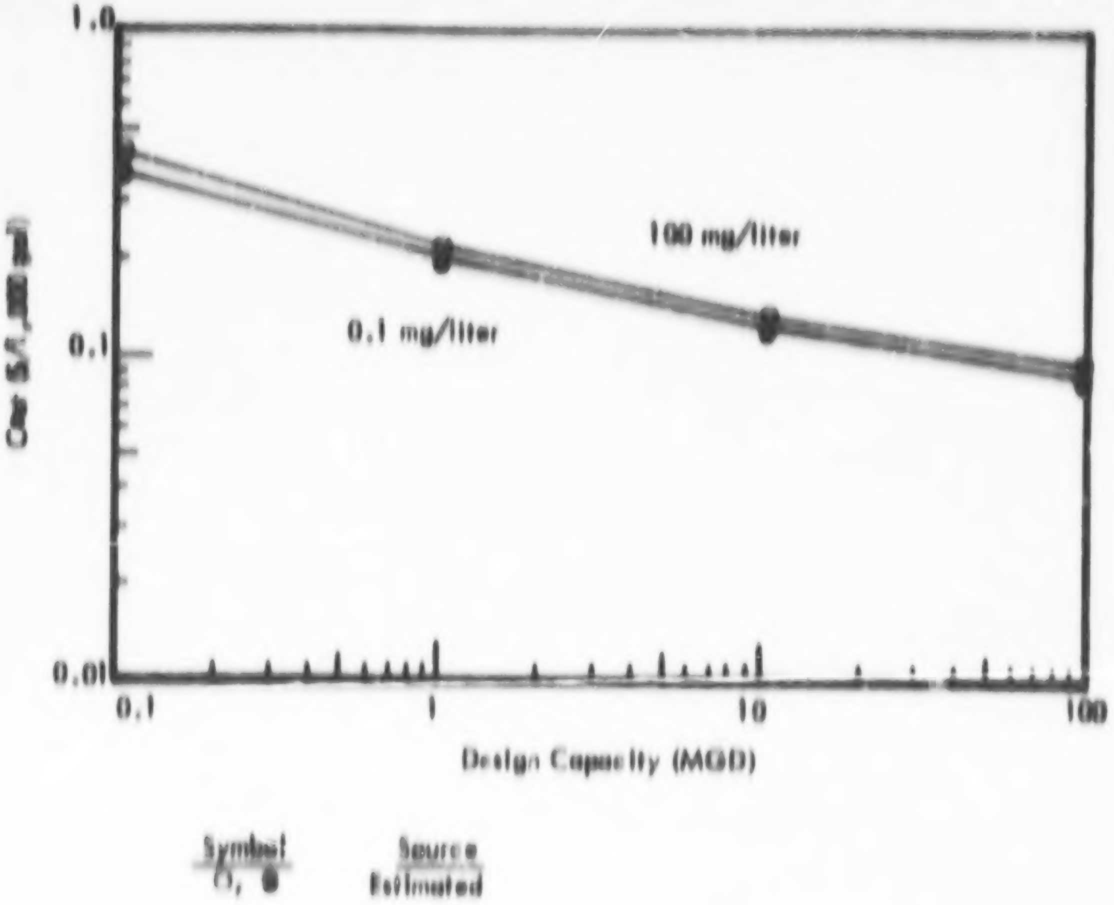


FIGURE A-17
ANTIMONY REMOVAL WITH HYDROGEN SULFIDE,
OPERATION AND MAINTENANCE COST RANGE
1974

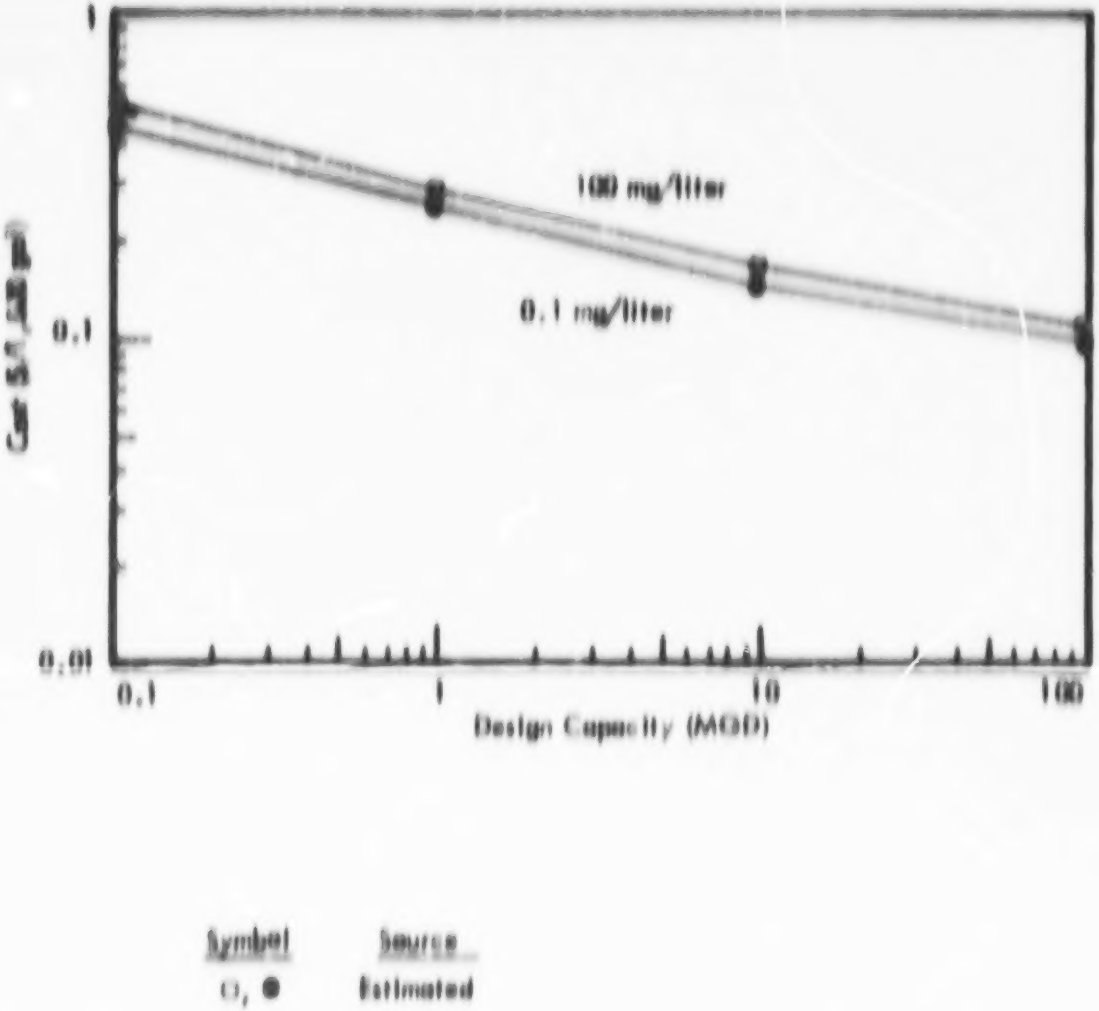


FIGURE A-13
ANTIMONY REMOVAL WITH HYDROGEN SULFIDE:
TOTAL COST RANGE
1974

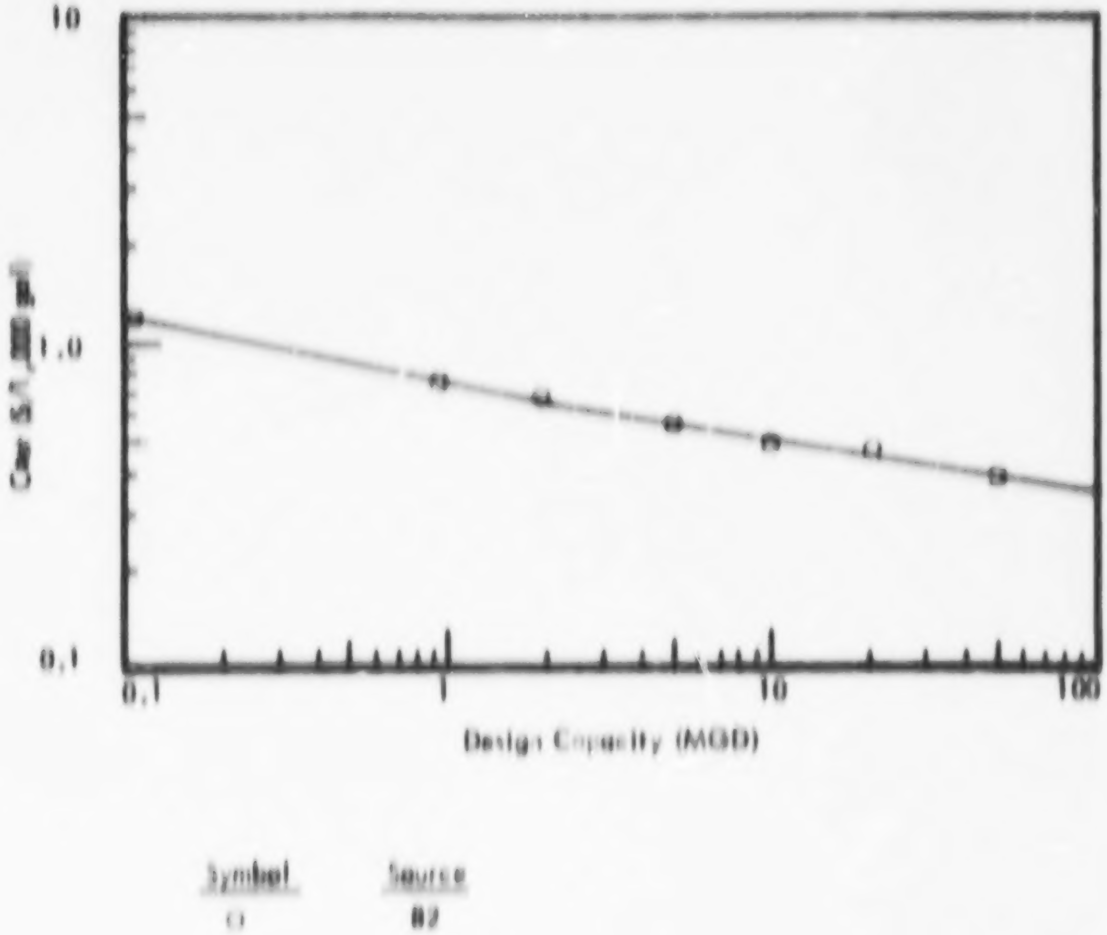
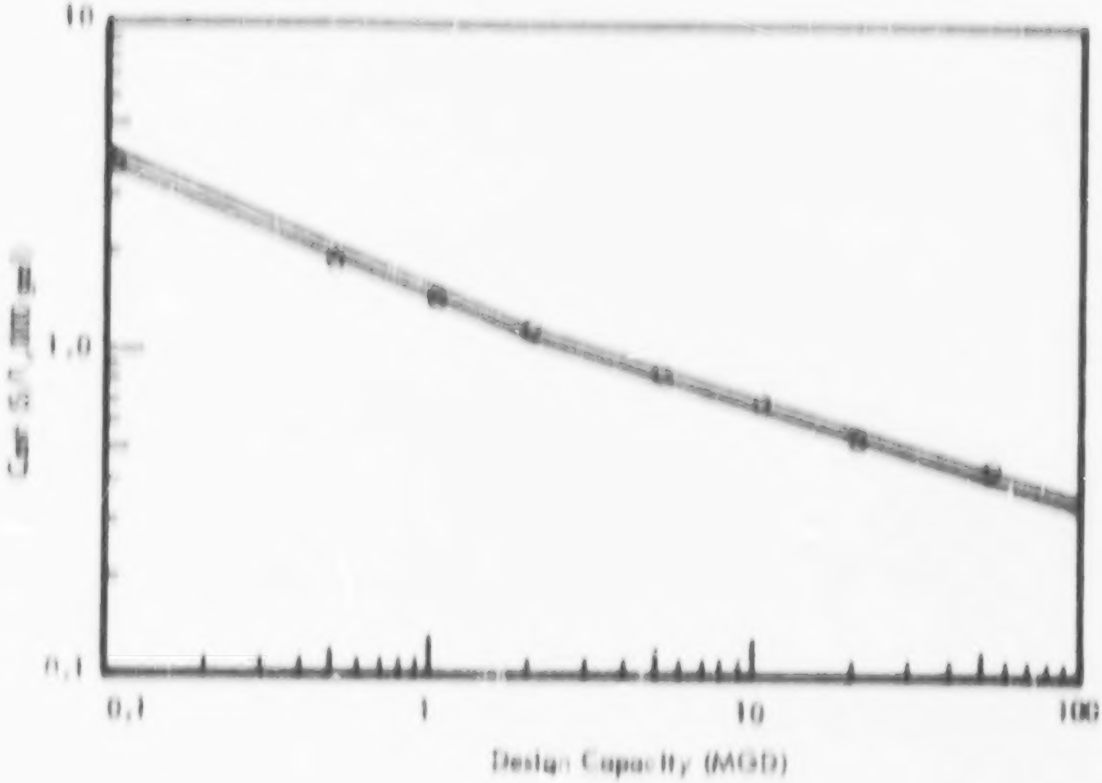
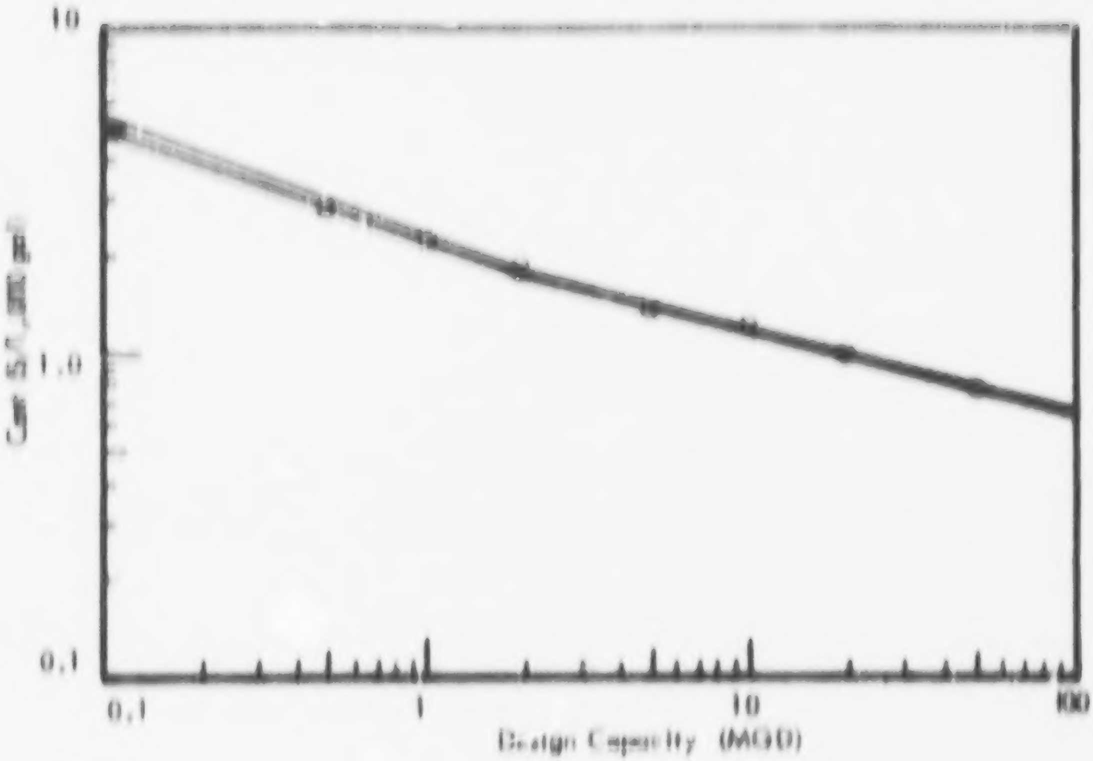


FIGURE A-14
DISTILLATION BY THE
MULTISTAGE FLASH PROCESS
CAPITAL COST
1974



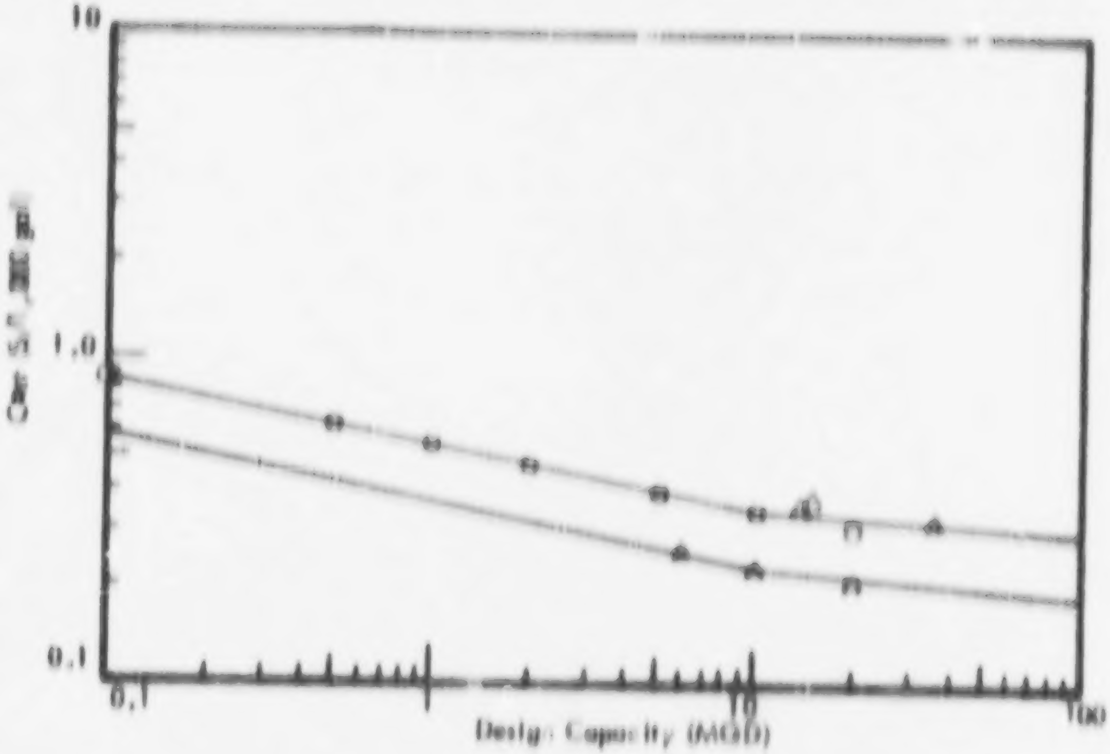
Symbol	Source
○	87

FIGURE A-15
DISTILLATION BY THE MULTISTAGE FLASH PROCESS:
OPERATION AND MAINTENANCE COST RANGE
1974



Symbol	Source
○	87

FIGURE A-16
DISTILLATION BY THE
MULTISTAGE FLASH PROCESS;
TOTAL COST RANGE
1974



Symbol	Source
○	87
△	83

FIGURE A-17
DISTILLATION BY THE COMBINED
VERTICAL COMPRESSION, VERTICAL TUBE EVAPORATION
MULTISTAGE FLASH PROCESS:
CAPITAL COST RANGE
1974

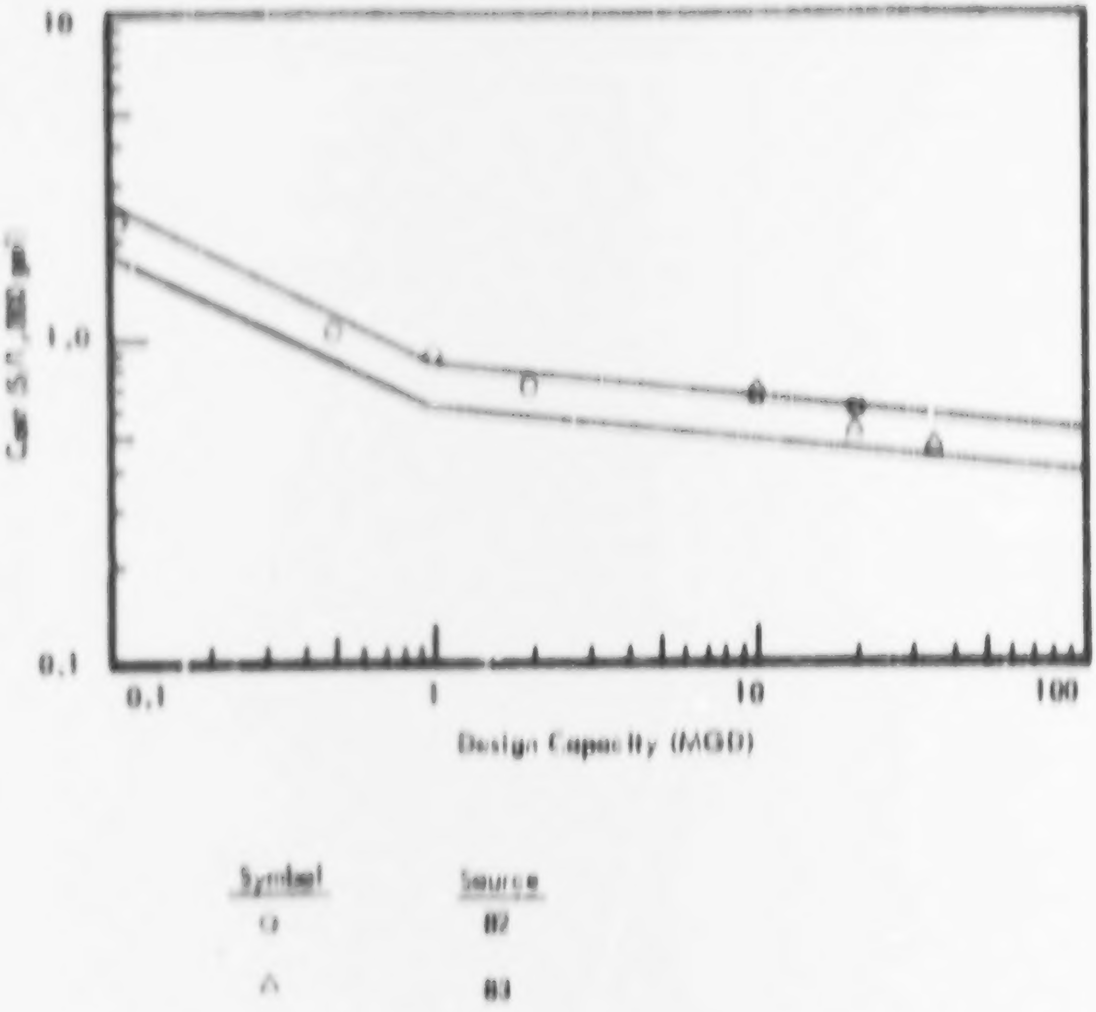
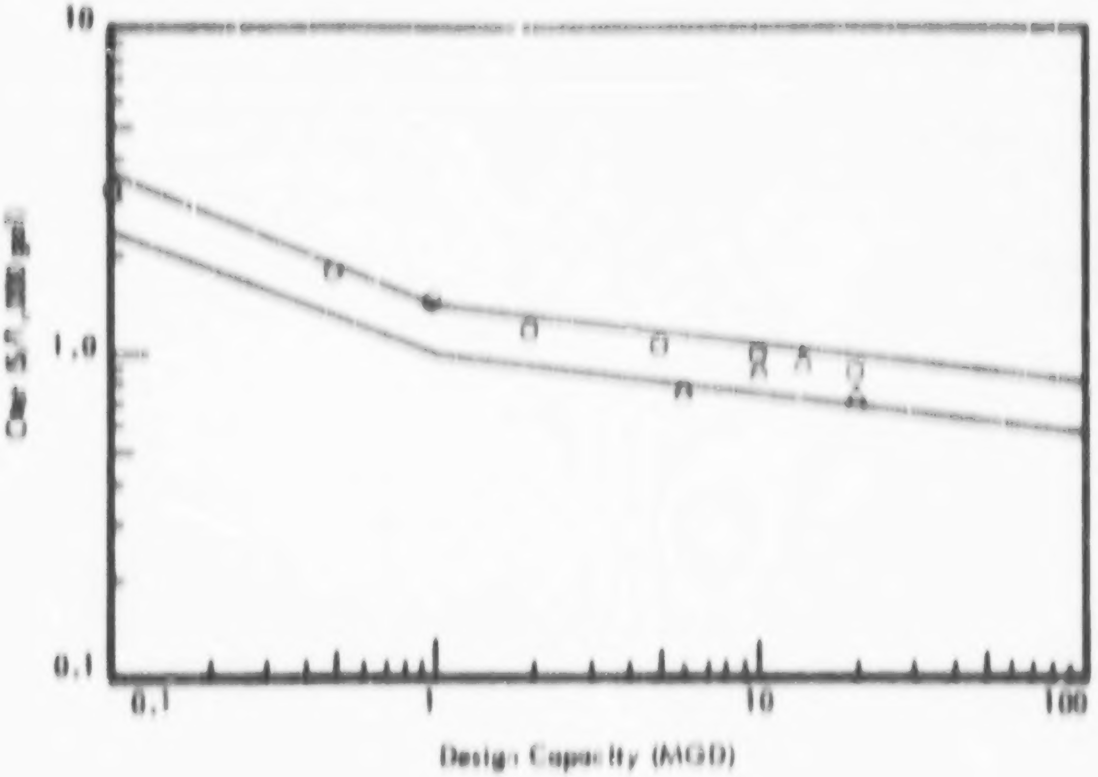
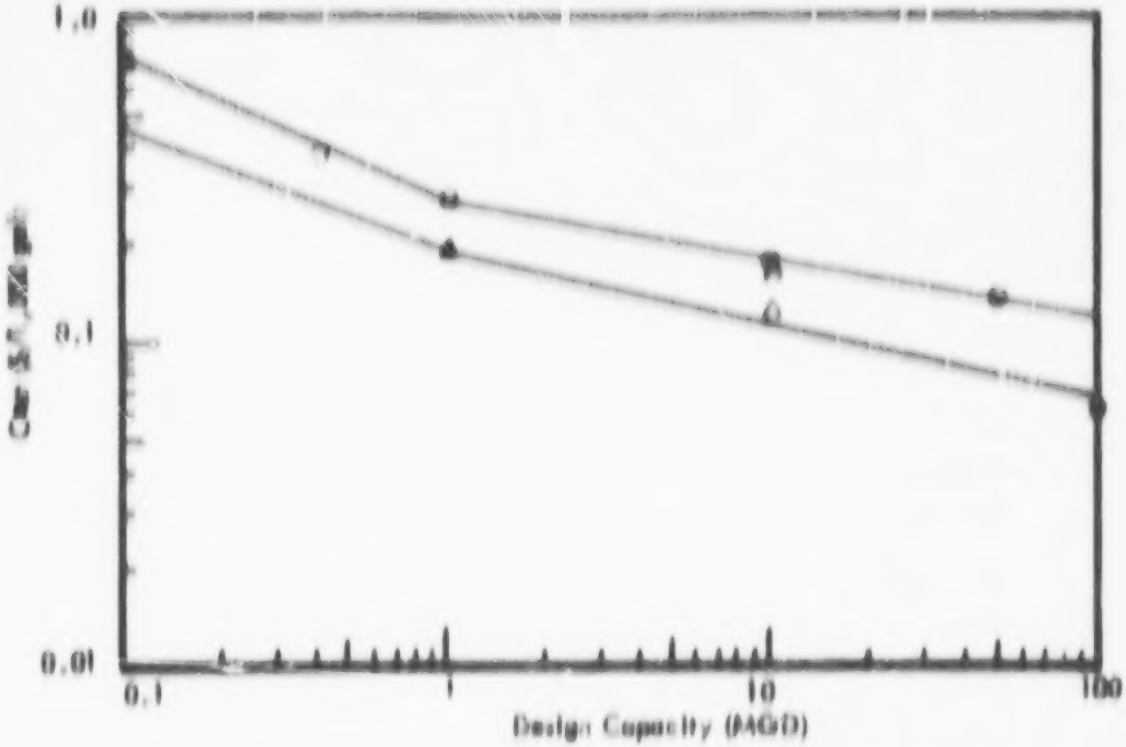


FIGURE A-18
DISTILLATION BY THE COMBINED
VAPOR COMPRESSION, VERTICAL TUBE EVAPORATION,
MULTISTAGE FLASH PROCESS:
OPERATION AND MAINTENANCE COST RANGE
1974



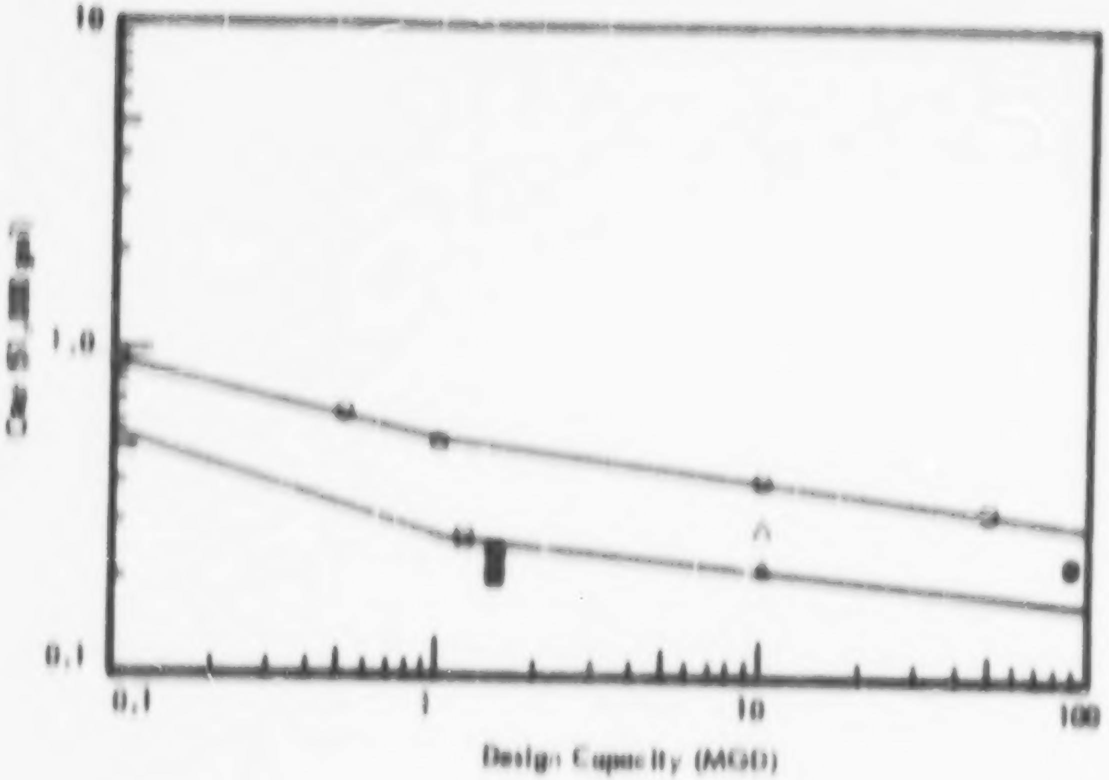
Symbol	Source
○	82
△	83

FIGURE A-19
DISTILLATION BY THE COMBINED
VAPOR COMPRESSION, VERTICAL TUBE EVAPORATION
MULTISTAGE FLASH PROCESS;
TOTAL COST RANGE
1974



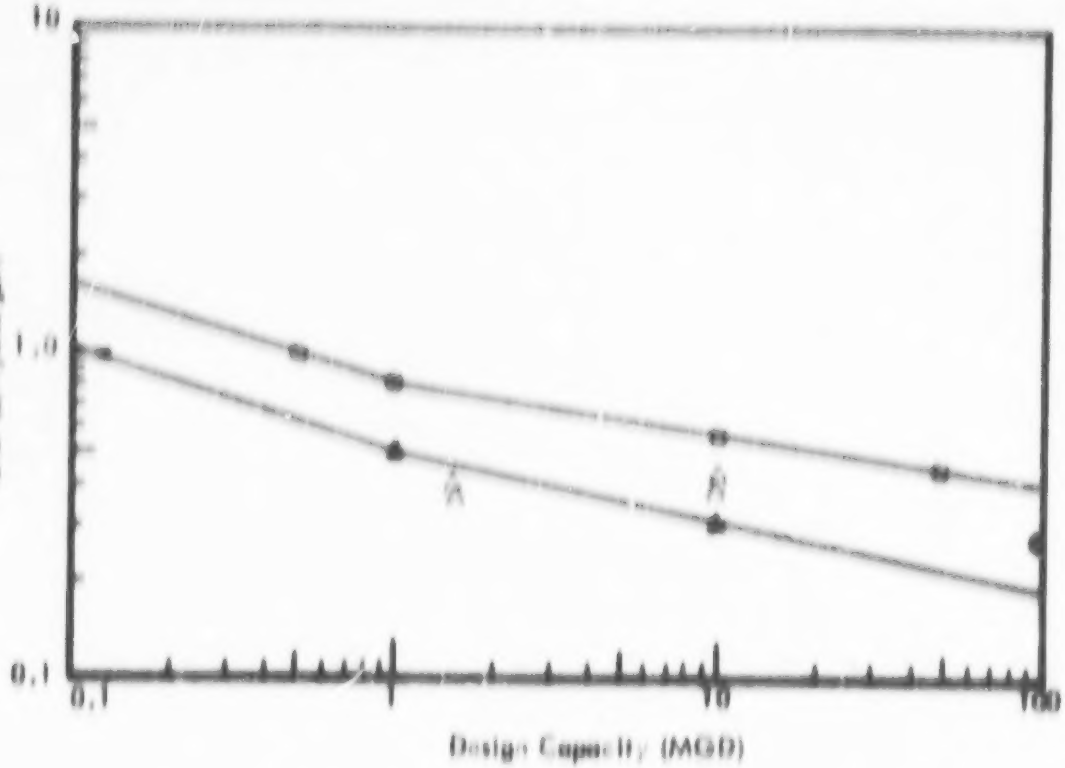
Symbol	Source
△	130
▲	88
○	116
●	148

FIGURE A-20
ELECTRODIALYSIS:
CAPITAL COST RANGE
1974



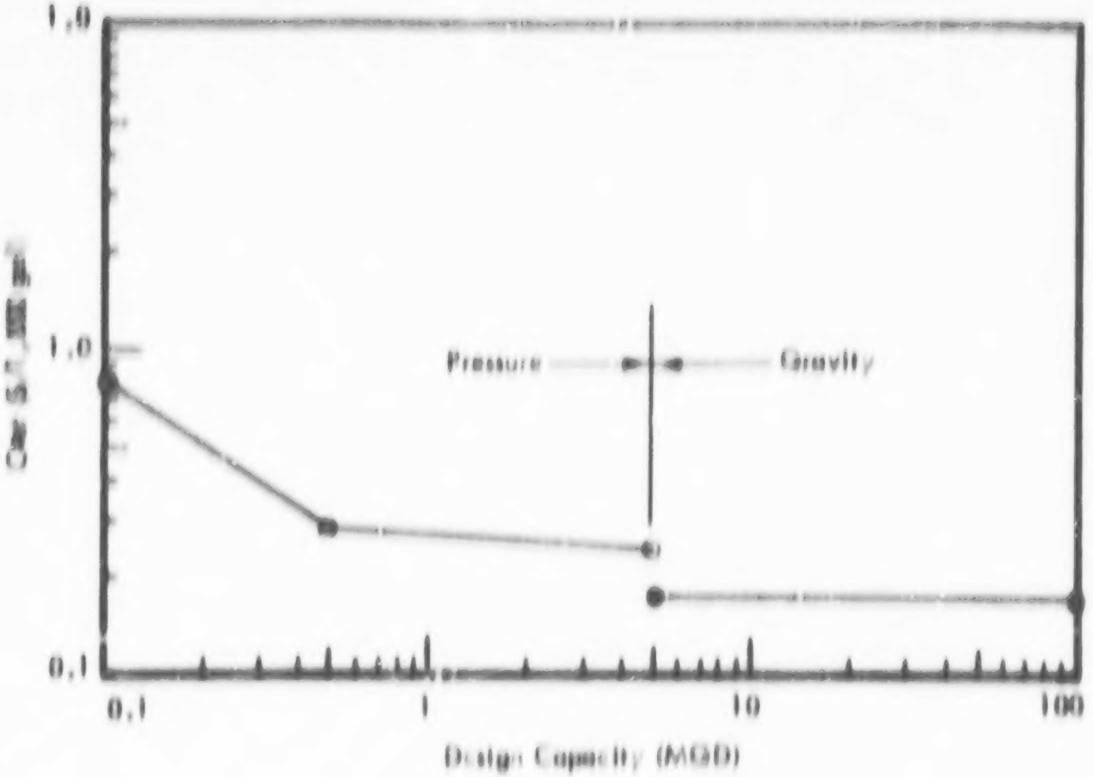
Symbol	Source
△	138
○	116
□	146
■	147
●	145

FIGURE A-21
ELECTRODIALYSIS:
OPERATION AND MAINTENANCE
COST RANGE
1974



Symbol	Source
△	138
▲	88
○	116
●	145

FIGURE A-27
ELECTRODIALYSIS:
TOTAL COST RANGE
1974



Symbol	Source
○ (Pressure)	96
● (Gravity)	Estimated

FIGURE A-23
ION EXCHANGE FOR ALL ELEMENTS;
CAPITAL COST
1974

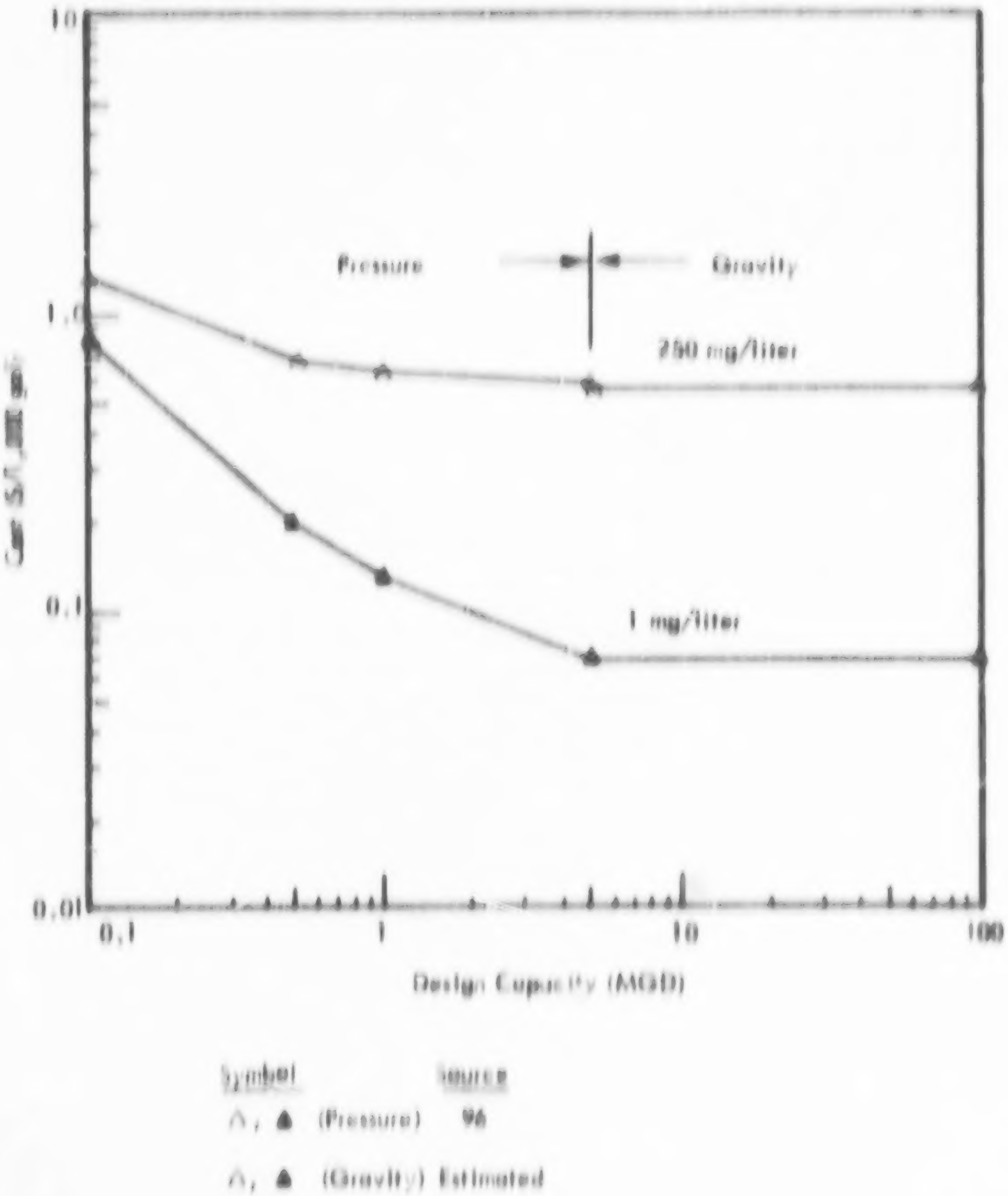
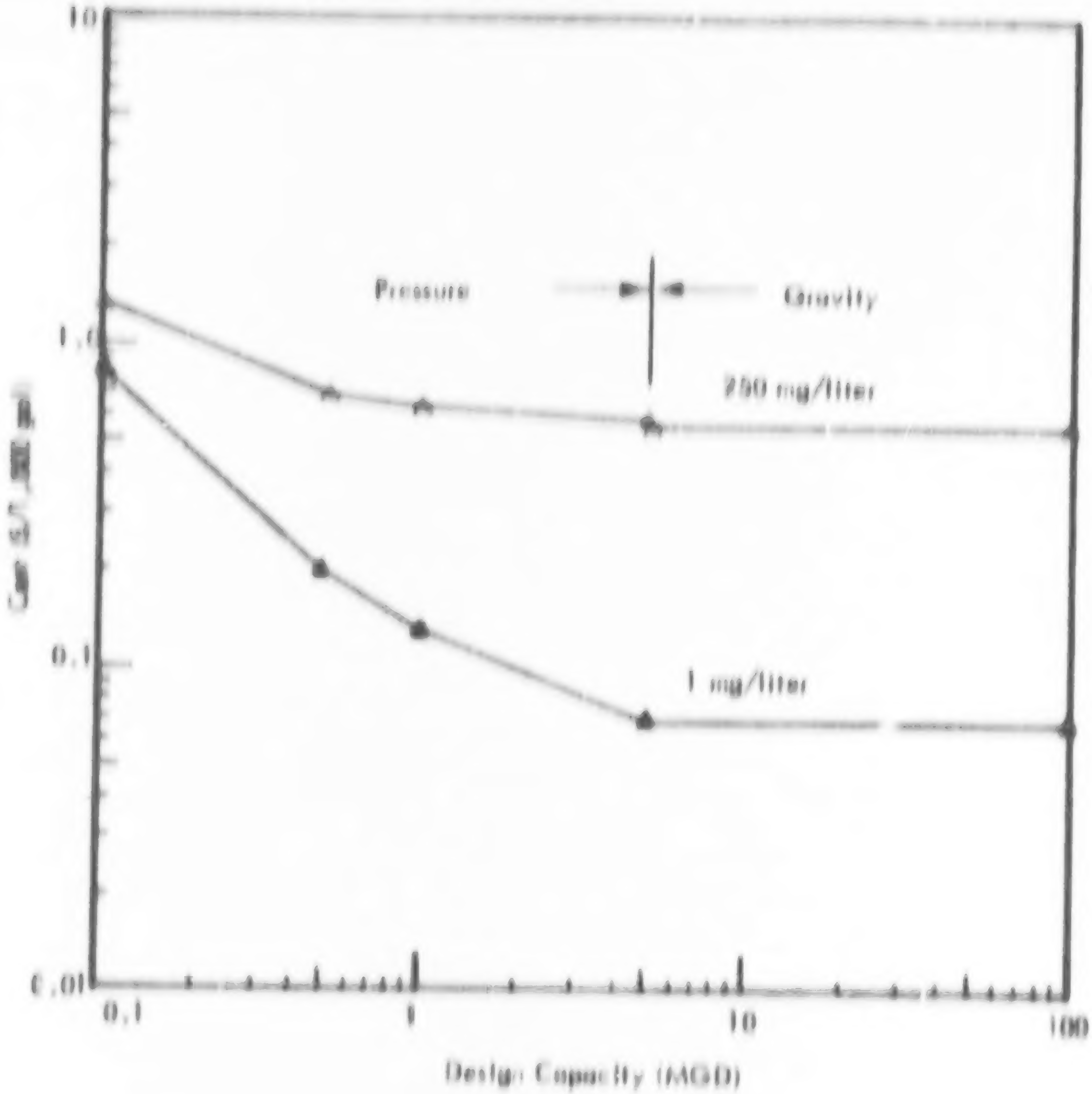
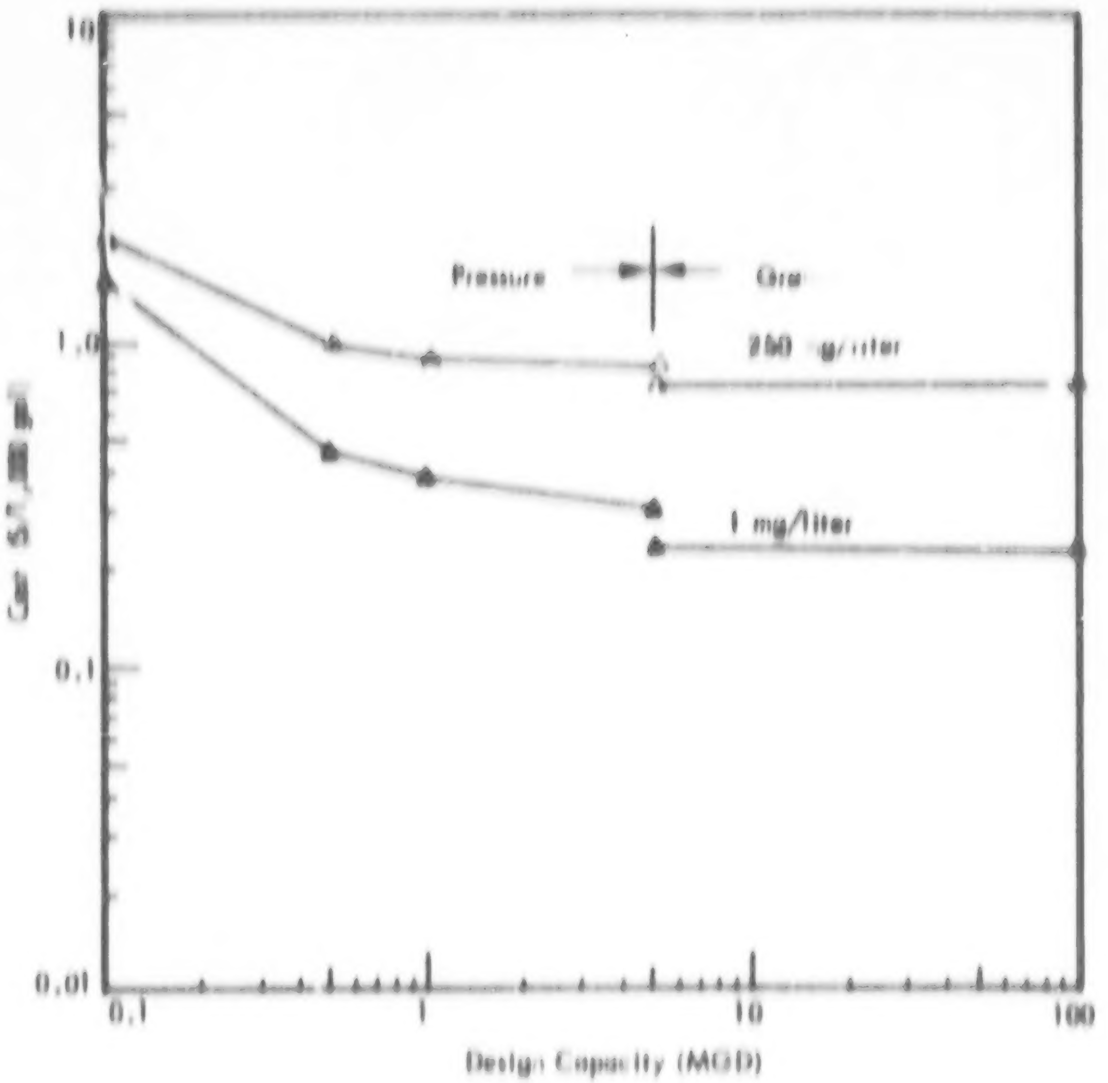


FIGURE A-24
ION EXCHANGE ANTIMONY AND VANADIUM:
OPERATION AND MAINTENANCE COST RANGE
1974



Symbol	Source
△, ▲ (Pressure)	96
△, ▲ (Gravity)	Estimated

FIGURE A-24
ION EXCHANGE, ANTIMONY AND VANADIUM;
OPERATION AND MAINTENANCE COST RANGE
1974



Symbol	Source
△, ▲ (Pressure)	96
△, ▲ (Gravity)	Estimated

FIGURE A-25
ION EXCHANGE, ANTIMONY AND VANADIUM,
TOTAL COST RANGE
1974

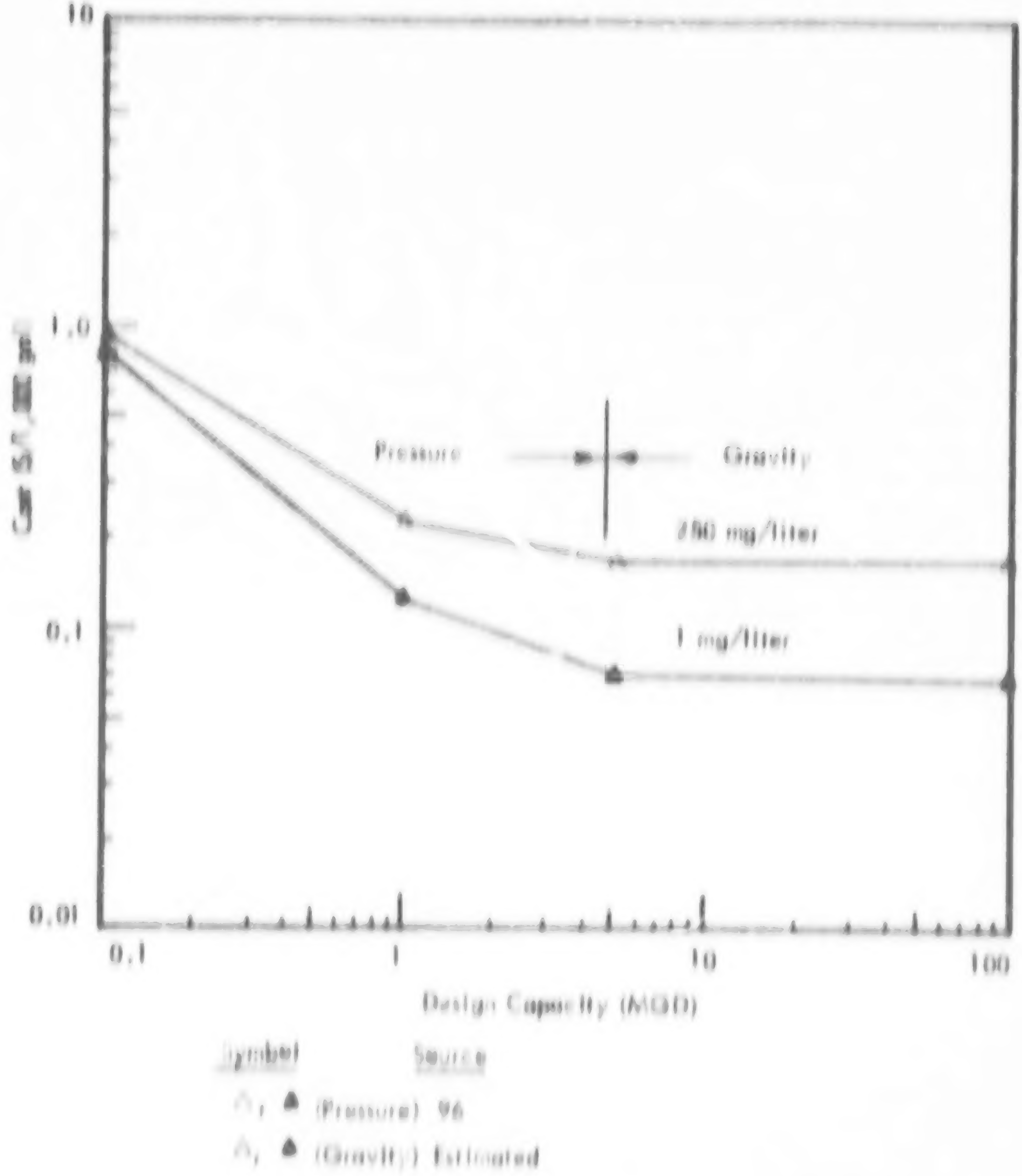


FIGURE A-26
ION EXCHANGE,BERYLLIUM;
OPERATION AND MAINTENANCE
COST RANGE
1974

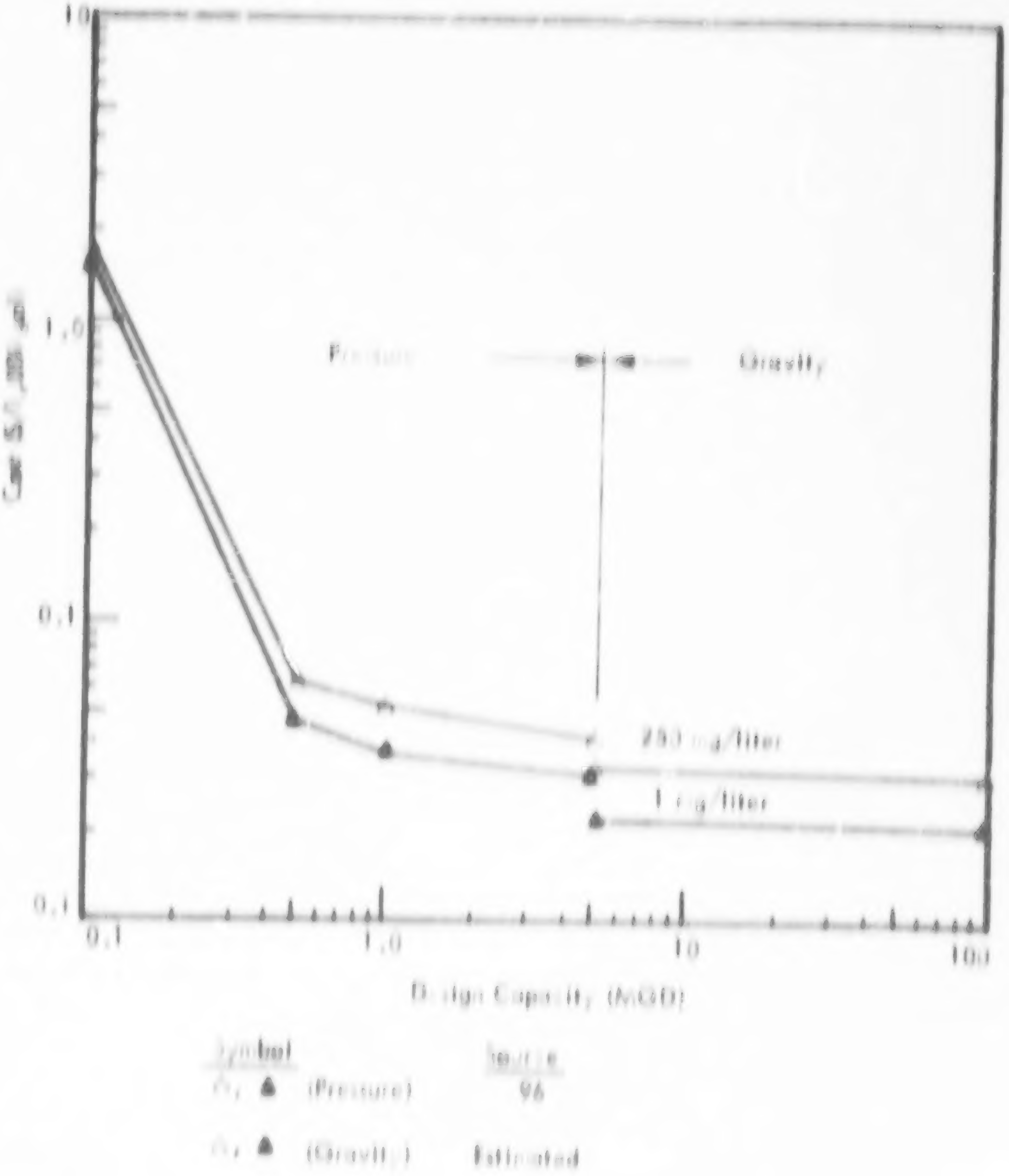


FIGURE A-27
ION EXCHANGE, BERYLLIUM,
TOTAL COST RANGE
1974

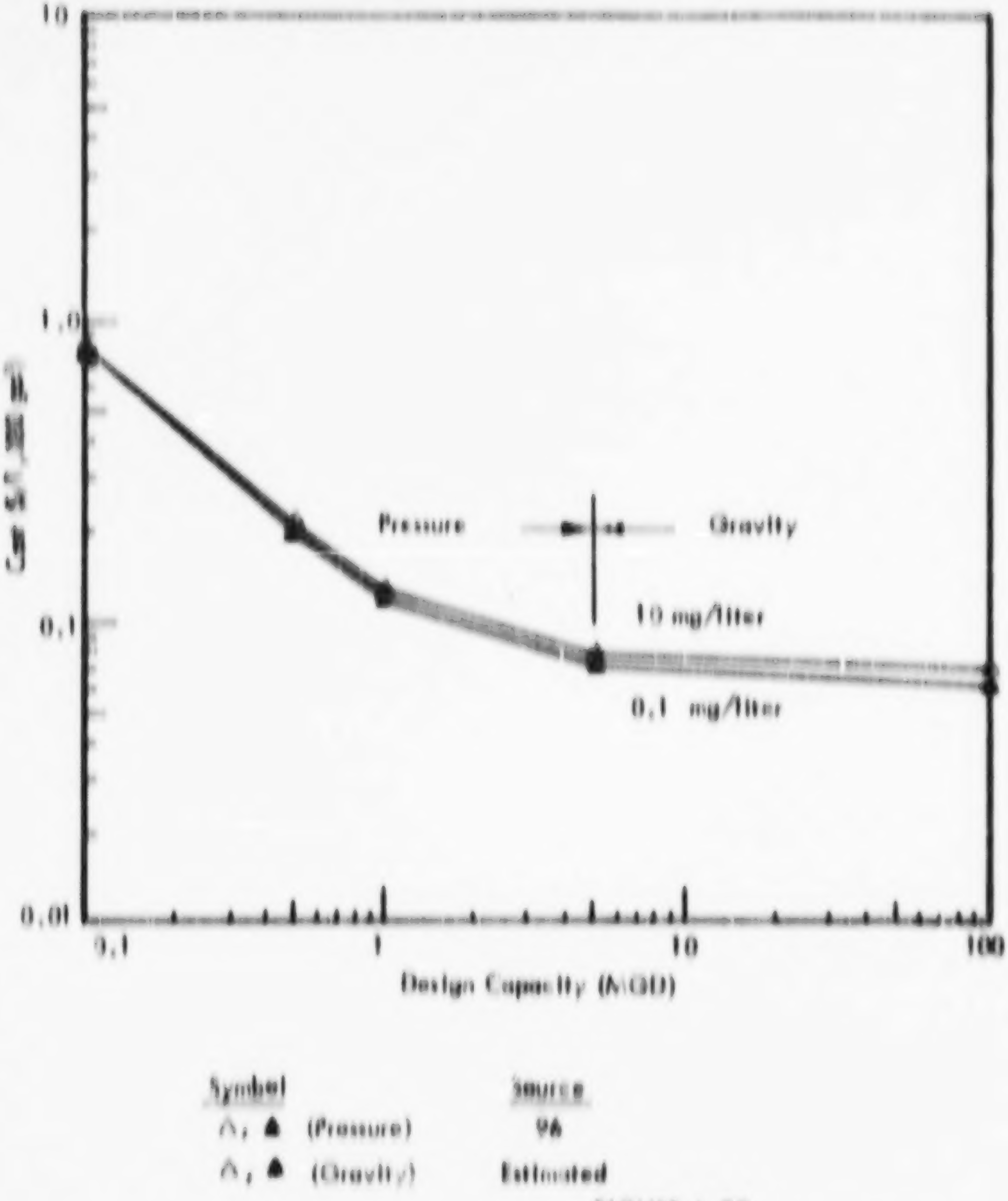


FIGURE A-28
ION EXCHANGE, COBALT AND NICKEL:
OPERATION AND MAINTENANCE
COST RANGE
1974

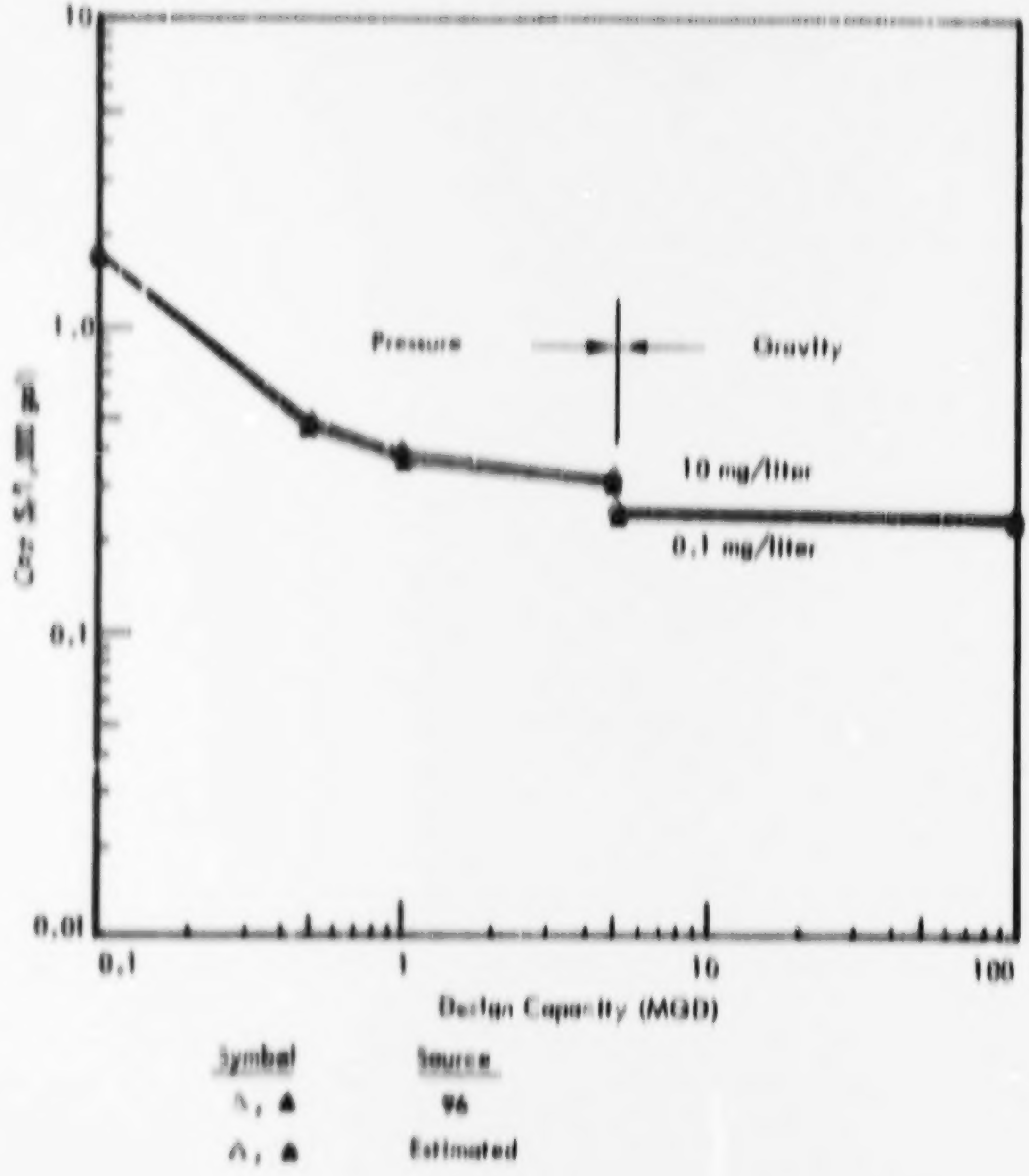


FIGURE A-29
ION EXCHANGE, COBALT AND NICKEL:
TOTAL COST RANGE
1974

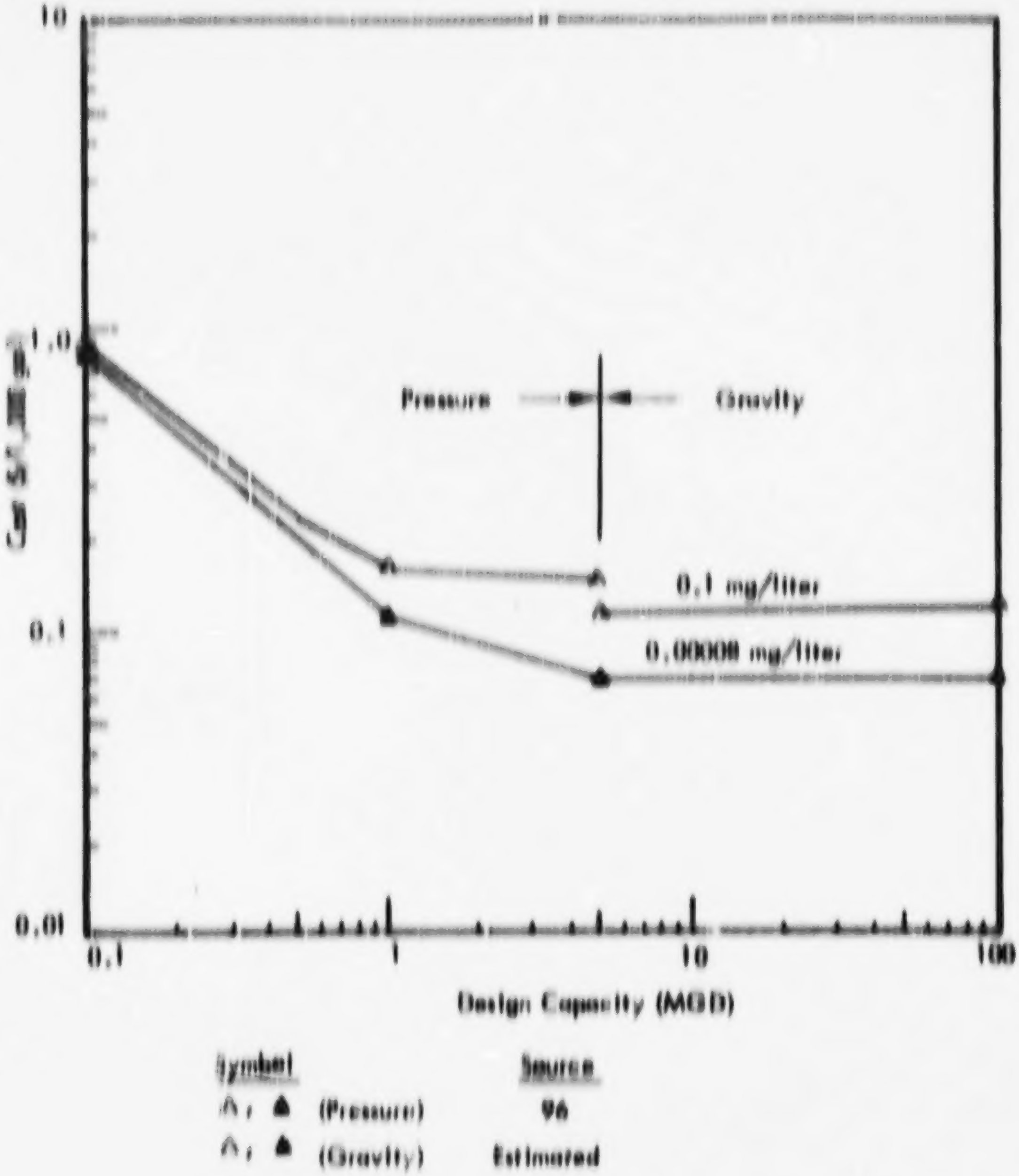


FIGURE A-80
ION EXCHANGE, LITHIUM;
OPERATION AND MAINTENANCE
COST RANGE
1974

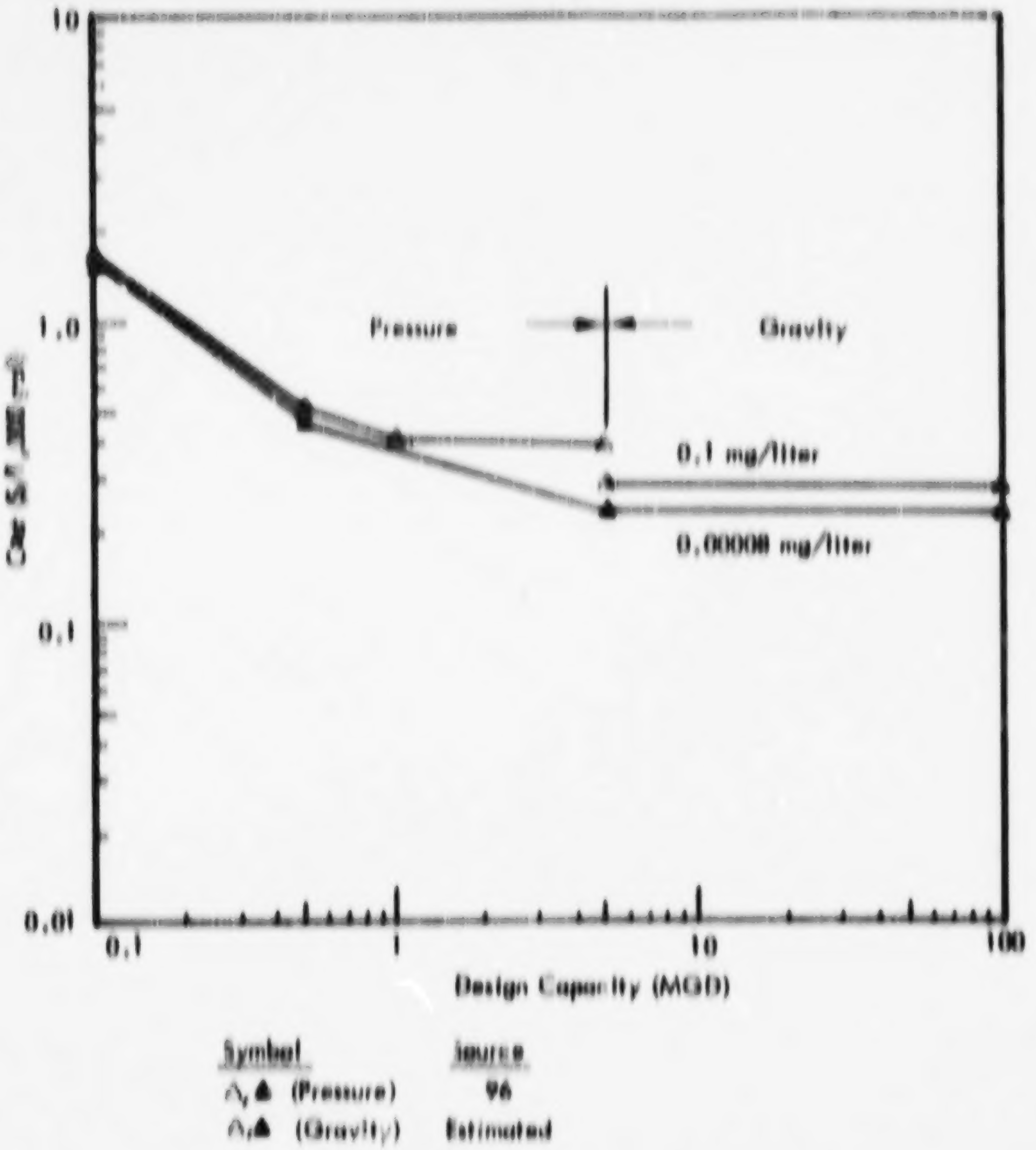
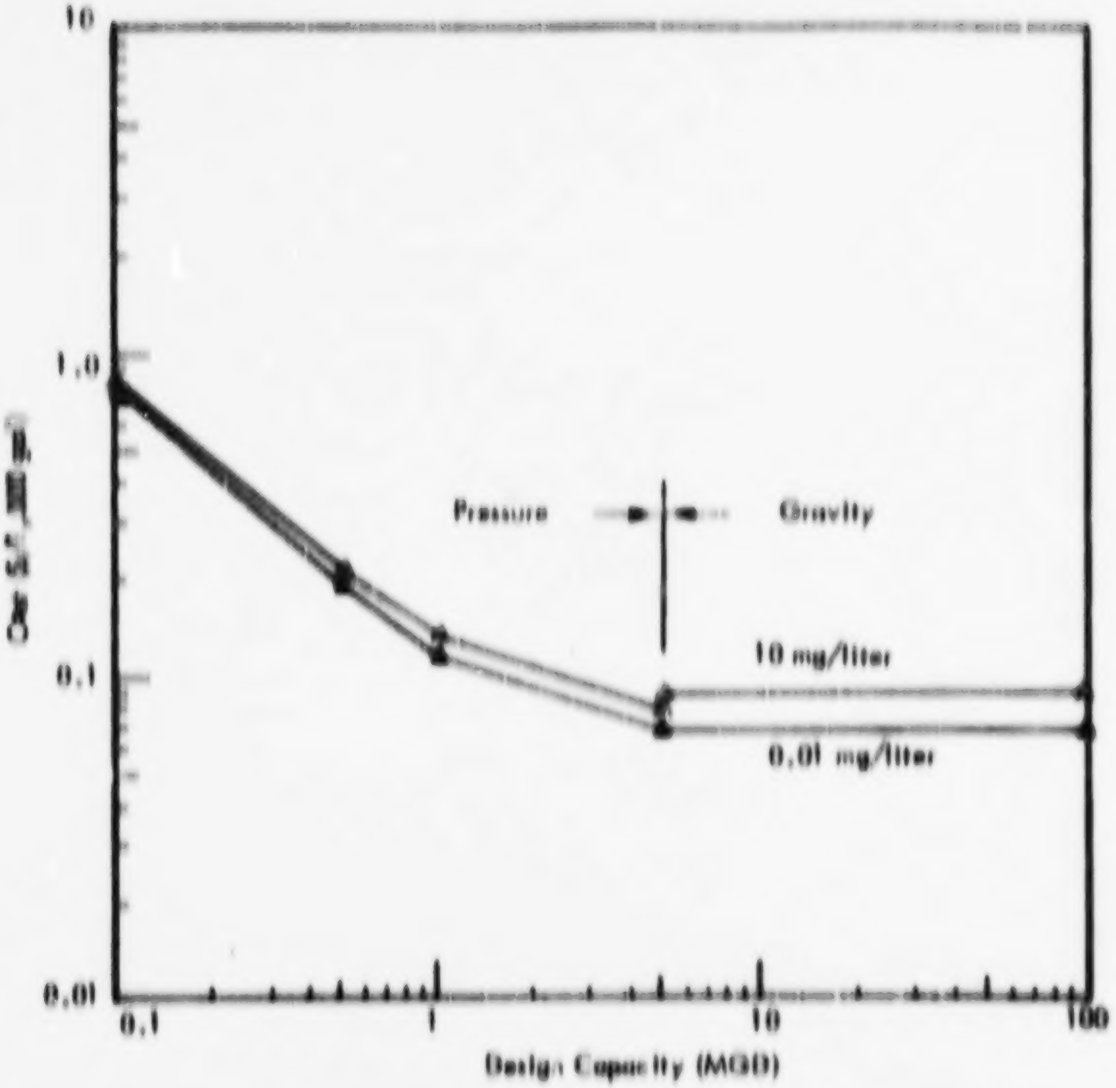


FIGURE A-31
ION EXCHANGE, LITHIUM:
TOTAL COST RANGE
1974



Symbol		Source
△, ▲	(Pressure)	96
△, ▲	(Gravity)	Estimated

FIGURE A-37
ION EXCHANGE, TUNGSTEN AND MOLYBDENUM;
OPERATION AND MAINTENANCE
COST RANGE
1974

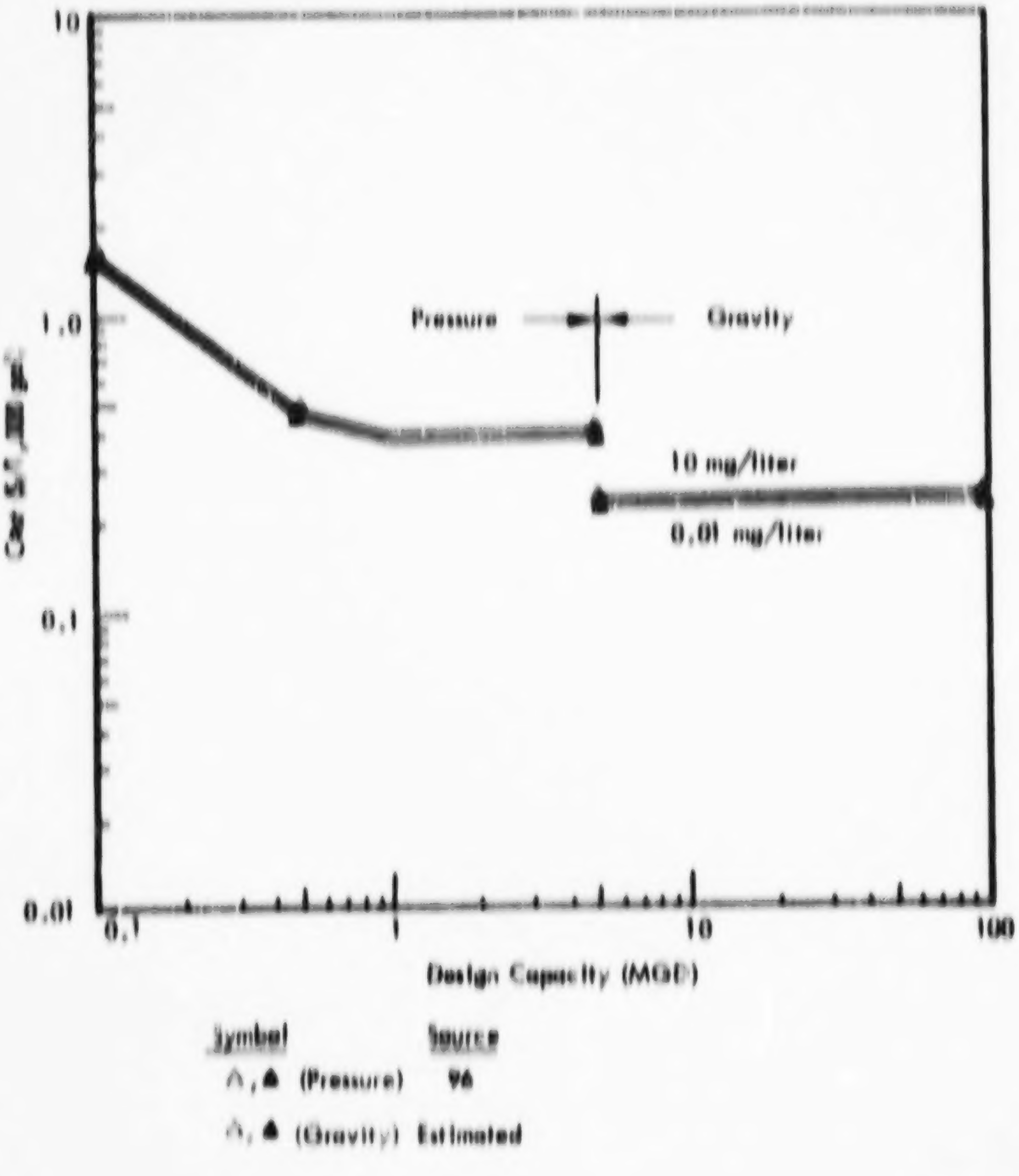


FIGURE A-33
ION EXCHANGE,TUNGSTEN AND MOLYBDENUM:
TOTAL COST RANGE
1974

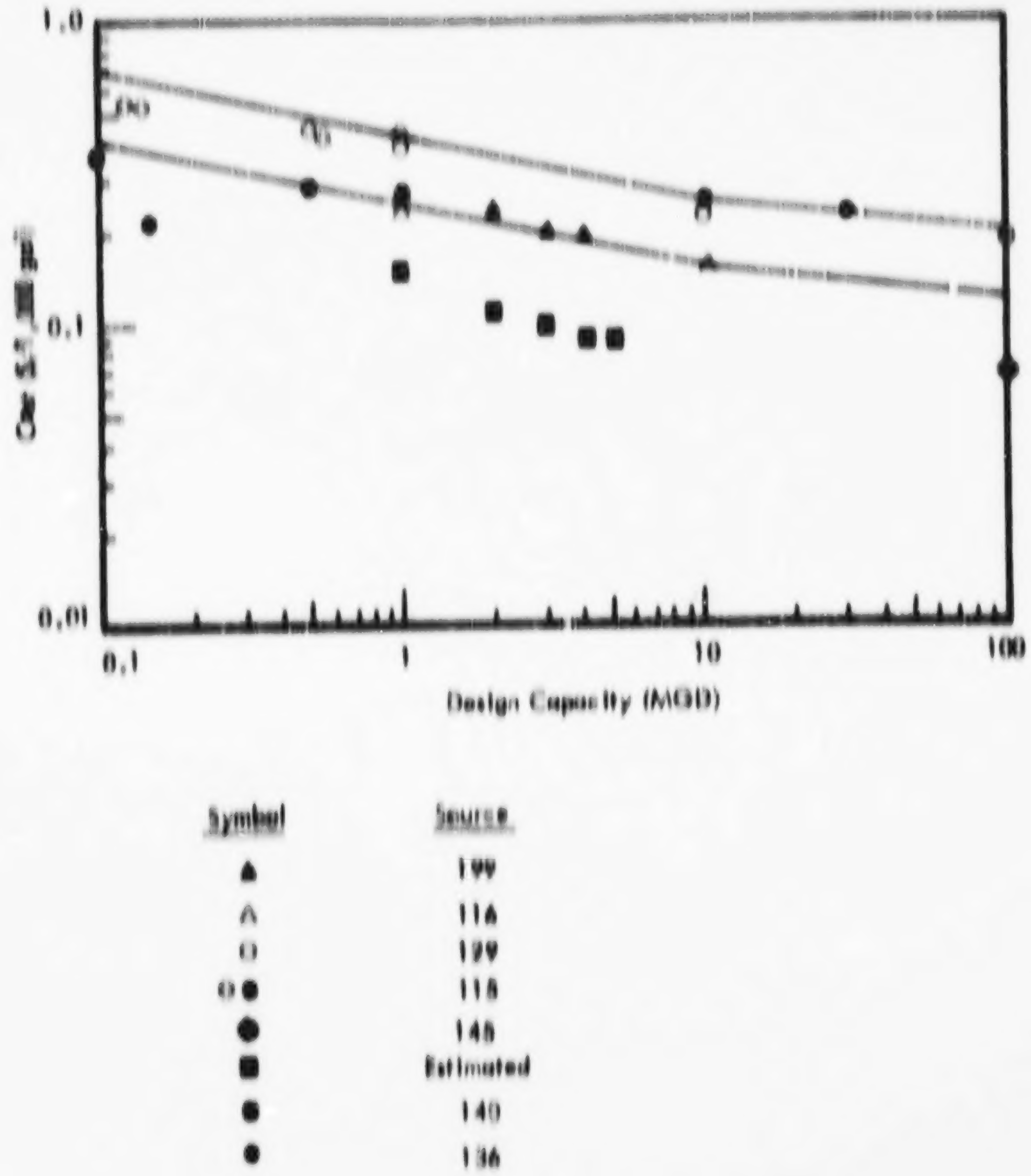
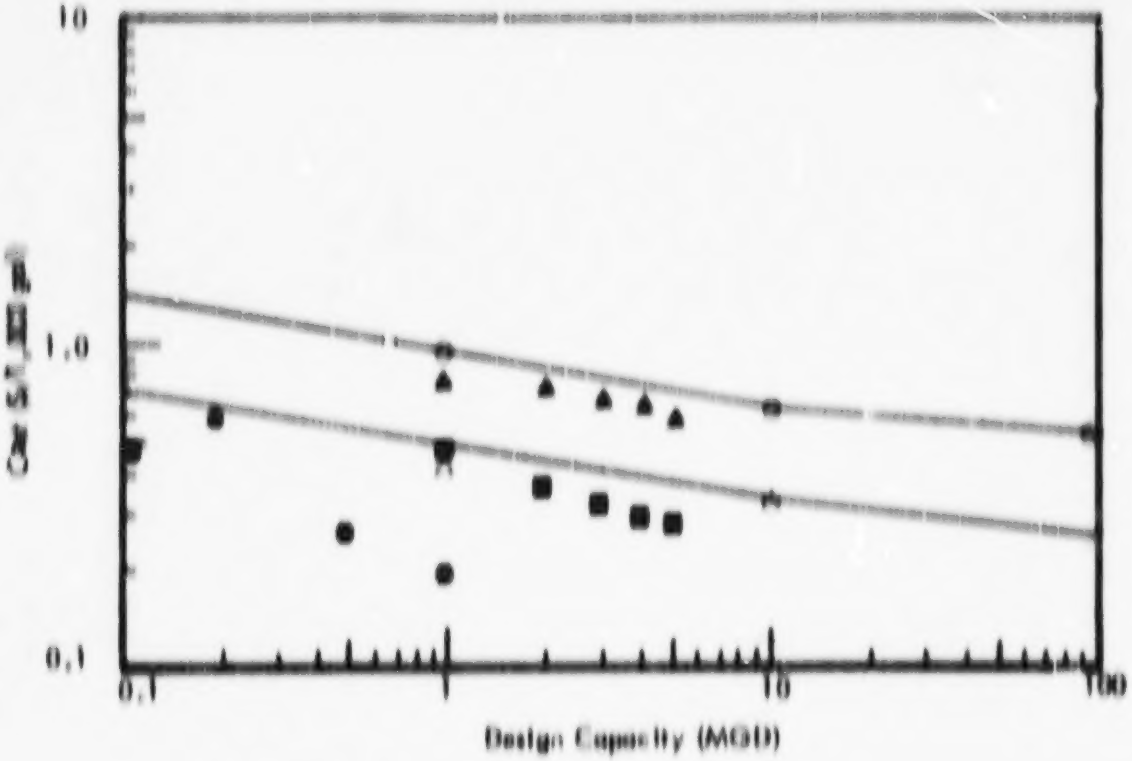
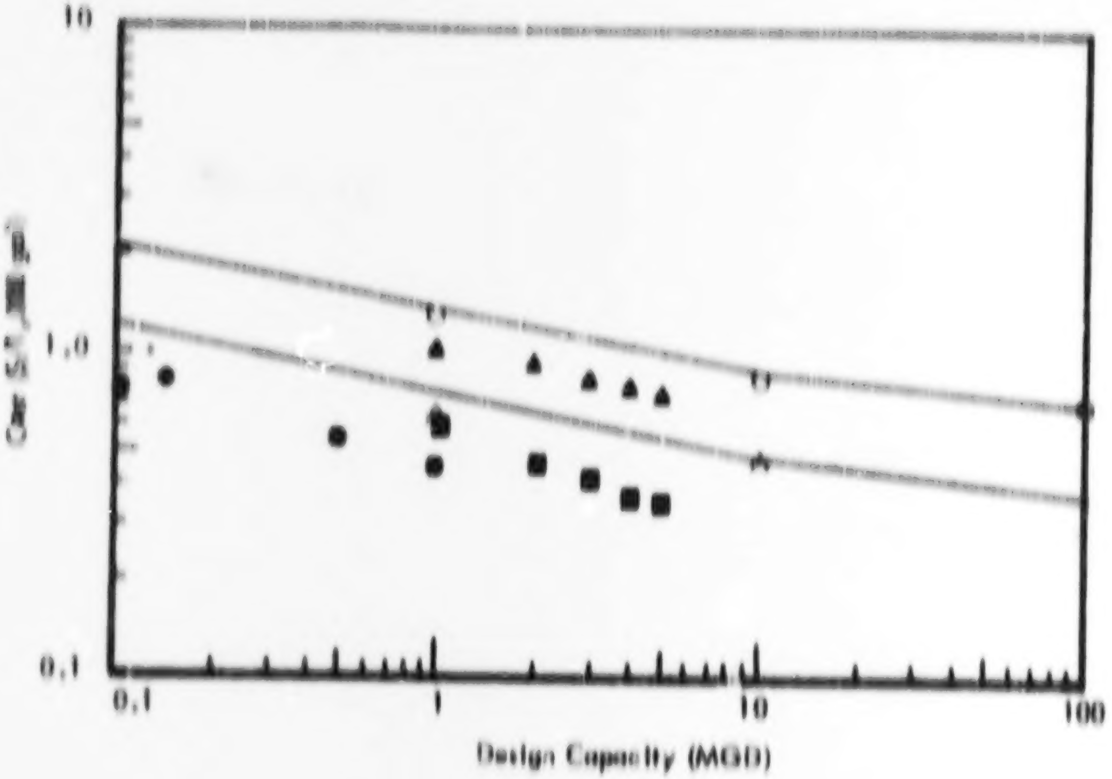


FIGURE A-34
REVERSE OSMOSIS:
CAPITAL COST RANGE
1974



Symbol	Source
▲	199
△	116
○	129
■	Estimated
●	140
●	136

FIGURE A-35
REVERSE OSMOSIS:
OPERATION AND MAINTENANCE
COST RANGE
1974



Symbol	Source
▲	199
△	116
○	129
■	Estimated
◉	40
●	136

FIGURE A-36
REVERSE OSMOSIS
TOTAL COST RANGE
1974